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AN OZONE CLIMATOLOGY OF THE DALLAS-FORT WORTH AREA AND ITS RELATIONSHIP TO METEOROLOGY

A Thesis

by

TIMOTHY EDWARD NOBIS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 1998

Major Subject: Meteorology

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ABSTRACT

An Ozone Climatology of the Dallas-Fort Worth Area and Its Relationship to Meteorology. (August 1998)

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The Environmental protection agency has established a National Ambient Air Quality Standard for surface ozone through the Clean Air Act and its amendments. The Dallas / Fort Worth area is in violation of these standards, and to date, no extensive studies on ozone in this area have been published. This study presents a broad overview of the ozone problem in the DFW area.

An ozone spatial and temporal climatology was constructed using ozone data at 23 different monitoring sites from 1980-1996. Temporally, the high ozone threat was found to extend from 16 Apr-15 Oct, a period one month longer than the traditional period used in cities further north. Strong persistence was found over synoptic time periods, consistent with studies in other cities. The spatial study was challenged by the lack of a consistent monitoring network, but in general relatively depressed ozone values are observed in urban areas, with increasing ozone values in rural areas especially downwind. Northern rural areas had the highest ozone averages.

Ozone - meteorology relationships were examined using scatterplots and correlation coefficients. Most of the meteorology variables only displayed a

rate-limiting role with ozone. Correlation values displayed significant seasonal variation, with temperature having a much lower correlation than expected based on results from other studies.

Conditional Climatology Tables were constructed to explore which combination of variables pointed to the highest ozone days. Yesterday's ozone, wind speed, and wind direction were found the most predictive. In general, low wind speeds and wind directions from the E-SE were most favorable for high ozone.

Wind direction biases were examined using windroses and by examining upwind vs. downwind behavior at the periphery sites. Evidence suggests that high ozone in the east, south, and west has occurred, but has gone undetected due to a lack of consistent monitoring there. There is also some evidence that winds from the E-SE may be transporting precursors from outside the DFW area, although further research is required.

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1. INTRODUCTION

Summertime surface ozone can reach levels unhealthy to both plants and humans in many U. S. urban and surrounding rural areas (National Research Council, 1992). The Environmental Protection Agency (EPA) has established a National Ambient Air Quality Standard (NAAQS) for ozone through the Clean Air Act and it's amendments. Areas that violate the NAAQS are designated non-attainment areas. The standard for current ozone non-attainment areas is based on an area having no monitor which measures more than one exceedence day per year averaged over three years of complete data. An exceedence day at a monitor is a day on which any hourly averaged ozone concentration exceeded 124 parts per billion (ppb). These areas are required to develop a plan to come back into attainment. Extensive research into the ozone problem of many non-attainment areas has linked high ozone potential with summertime stagnate anticyclonic air masses. However, specific ozone climatology and meteorological relationships show considerable variation between different regions of the country.

The Dallas / Fort Worth (DFW) area is designated as a non-attainment area by the EPA and ozone activity has been monitored since 1973. To date no extensive ozone and meteorology relationship studies have been conducted in this area. The DFW area could benefit from such a study as part of its efforts to reach attainment. Furthermore, results from some regional studies (Chameides and Cowling, 1995; Eder et al., 1993; and Cox and Chu, 1993) suggests that the behavior of ozone and it's relationship with meteorology

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This thesis follows the style and format of *Atmospheric Environment*.

may be quite different in southern areas of the United States as compared to behavior in the northern areas.

The purpose of this study is to present a basic analysis of the DFW ozone problem and compare characteristics of this problem with studies of ozone problems in other parts of the country. It is hoped that such a study will expose areas for further research and assess the DFW area's suitability for field projects and area studies. Specifically in this study, the spatial and temporal behavior of ozone will be examined to define a high ozone 'season', explore the episodic nature of ozone in the DFW area, and to characterize the behavior of the 'urban plume'. The general relationship between ozone and meteorology will be examined through correlation and scatterplots in an effort to highlight differences with northern cities. Conditional Climatology (CC) Tables will be constructed as a tool for exploring the combination of factors important to the development of high (> 104 and 124 ppb) ozone. Use of these tables provides a simple way to inspect what combination of meteorological factors are important and will help point out potential network and other non-meteorological biases. Finally, a brief examination of transport issues will be conducted to explore the potential impact of long-range transport of ozone and precursors upon the DFW area.

2. BACKGROUND

The following sections will provide background information including a brief overview of ozone chemistry, results from other studies, and the precursor distribution of the DFW area.

2.1. Basic Ozone Chemistry

In order to understand the behavior of ozone within an urban environment it is essential to develop an understanding of the formation of ozone. Ozone chemistry in the atmosphere is very complex with several cycles, numerous feedbacks, and a great amount of sensitivity to the environment in which the reactions are taking place. Understanding these cycles is the basis of much current research. What follows is a basic outline of ozone chemistry.

2.1.1. The NO_x Cycle

Ozone is formed when molecular oxygen unites with an oxygen atom in its ground electronic state in the presence of a third body:

$$O_2 + O(^3P) + M \rightarrow O_3 + M \tag{1}$$

Here M represents a stable third body (usually N_2 in our atmosphere) that helps dissipate the energy of the newly created O_3 molecule allowing it to stabilize and $O(^3P)$ is the ground state oxygen atom. There are no significant sources of ozone in the atmosphere other than this reaction (Seinfeld, 1986).

The source of the ground state oxygen atom in the troposphere is the photo-dissociation of NO_2:

$$NO_2 + hv \rightarrow O(^3P) + NO \tag{2}$$

Here hv represents ultraviolet light less than 430nm (Brimblecombe, 1996). The combination of NO_2 and NO are referred to as NO_x. The NRC (1992)

concluded that in the troposphere, ozone formation occurs to any significant extent only from the photolysis of NO_2. Thus, the availability of sunlight and NO_2 are critical for O_3 production.

To close this cycle, ozone reacts with nitric oxide forming oxygen and nitrogen dioxide:

$$O_3 + NO \rightarrow O_2 + NO_2 \qquad (3)$$

This reaction is sometimes referred to as the titration or chemical scavenging of ozone.

This reaction cycle (equations 1-3) will come to a steady state. The amount of O_3 maintained at steady state is based on the initial NO_2/NO ratio. Seinfeld (1986) showed that if the starting ozone value is zero, the maximum steady state ozone concentration would be achieved with an initial charge of pure NO_2. However, in the troposphere, most of the NO_x released is in the form of NO. From the above cycle, reaction rate calculations with realistic atmospheric amounts of NO_x, show that predicted O_3 concentrations fail to reach observed atmospheric values. Brimblecombe (1986) considered the observed daily progression of NO, NO_2, and O_3 in the urban atmosphere. If only equations 1-3 are responsible for ozone production, then as morning progresses NO_2 should undergo photolysis, thereby decreasing from the initial charge and approximately equal amounts of O_3 and NO should be created. But when observed in real atmospheres, NO levels rise very fast in the early morning and then fall to near zero by midday, ozone shows a slower but steady increase throughout the morning, and amounts of NO_2 increase then peak in the mid-morning hours. The same results are obtained in smog chambers under

controlled conditions precluding daytime emissions from accounting for the observations.

Clearly, equations 1-3 acting alone cannot account for the observed values or behavior of NO_x and ozone. Since NO_2 is the key to O_3 production, some other cycle or cycles must be enhancing the NO_2 levels of the atmosphere allowing the enhancement of O_3 levels. There is a group of reactive carbon based compounds produced both naturally and as a result of anthropogenic activities. They are known collectively as Volatile Organic Carbons (VOC's), and are the key to NO_2 enhancement.

2.1.2. The Influence of VOC's on Ozone Formation Rates Using Formaldehyde as an Example

Formaldehyde (HCHO) is a very common and relatively simple VOC. It is both a primary pollutant and is also a by-product of other tropospheric chemistry. It undergoes both photolysis and oxidation. All of this makes it an ideal example to illustrate the role of VOC's in ozone formation.

Formaldehyde will undergo photolysis by two routes. In the first reaction sequence:

$$HCHO + hv \rightarrow H\bullet + HCO\bullet \tag{4}$$

Here the dot (•) identifies a radical species. The H• will quickly react with O_2:

$$H\bullet + O_2 \rightarrow HO_2\bullet \tag{5}$$

yielding a net reaction of:

$$HCHO + hv + O_2 \rightarrow HO_2\bullet + HCO\bullet \tag{6}$$

In the second reaction:

$$HCHO + hv \rightarrow CO + H_2 \tag{7}$$

Formaldehyde will also react with the hydroxyl radical:

$$HCHO + OH\bullet \rightarrow HCO\bullet + H_2O \qquad (8)$$

The $HCO\bullet$ from equations 6 and 8 will undergo further reaction:

$$HCO\bullet + O_2 \rightarrow HO_2\bullet + CO \qquad (9)$$

Whether by equation 6 or 8-9, the net result is the creation of the hydroperoxyl radical ($HO_2\bullet$). This radical will react with NO:

$$HO_2\bullet + NO \rightarrow NO_2 + OH\bullet \qquad (10)$$

Thus the breakdown of HCHO can lead to the enhancement of NO_2 and ultimately ozone. A couple of things worth noting about these reaction sequences: First, a hydroxyl radical ($OH\bullet$) is created when NO is oxidized in equation 10 allowing the potential breakdown of more HCHO. Second, equation 10 requires the presence of NO in order to enhance NO_2. If NO is not present, the hydroperxyl radical will react with other compounds (including ozone), NO_2 levels will not be enhanced, and ozone values are likely to decrease. Estimates of the minimum amount of NO required to enhance ozone levels ranges from 5 ppt (Crutzen, 1988) to 30 ppt (NRC, 1992). NO in a polluted urban atmosphere is normally measurable in ppb during the day, so ozone is generally enhanced by the presence of VOC's. In the remote ocean boundary layer, NO values are generally below the minimum threshold, and ozone levels are depressed by the reaction of VOC's.

As discussed earlier, if just equations 1-3 are considered, NO values should increase at approximately the same rate as O_3, and NO_2 should steadily decrease, but this is not what we observe in the urban atmosphere. Now we can see that the values of NO fall off by midday because reactions like equation 10 are drawing NO levels down. Also we can see VOC reactions are

the reason for increasing levels of NO_2. Ozone levels then rise, as the increasing reservoir of NO_2 is photo-dissociated via equation 2.

2.1.3. The Hydroxyl Radical

As seen above, the hydroxyl radical plays a key role in oxidizing VOC's. What is the ultimate source of this radical? Ozone will photo-dissociate in the presence of ultraviolet light. Two types of photo-dissociation occur:

$$O_3 + hv \rightarrow O(^3P) + O_2 \text{ for } hv > 315\text{nm} \tag{11}$$

$$O_3 + hv \rightarrow O(^1D) + O_2 \text{ for } hv < 315\text{nm} \tag{12}$$

$O(^3P)$ will quickly react with an oxygen molecule to reform O_3. The $O(^1D)$ is an excited oxygen atom and is unable to reform O_3 in this state. Some of these excited atoms will react with water:

$$O(^1D) + H_2O \rightarrow 2OH\bullet \tag{13}$$

there-by forming the hydroxyl radical needed to start reactions like equation 8, and in effect, closing the cycles described above. It is here that we see the importance of ozone to tropospheric chemistry. Hydroxyl radicals are essential ingredients to the breakdown of VOC's and several other trace species.

2.1.4. General Photochemistry of the Polluted Atmosphere

In the polluted atmosphere, formaldehyde is not the only VOC present. There are several other carbon species which have a reaction sequence similar to equations 4-10, leading to NO_2 production. Seinfeld and Pandis (1998) report that current inventories identify more than 600 different anthropogenic VOC's in the urban atmosphere. This increased number of precursors greatly complicates the ozone production. The NRC (1992) summarizes these VOC sequences as follows:

$$VOC + (hv, OH\bullet) \rightarrow \alpha RO_2\bullet \tag{14}$$

The $RO_2\bullet$ represents a generic peroxy radical. (In the formaldehyde example, $HO_2\bullet$ was the peroxy radical created.) The number (α) of peroxy radicals produced on a per molecule basis will differ from VOC to VOC. These radicals then react:

$$\alpha RO_2\bullet + \beta NO \rightarrow \delta NO_2 + \phi OH\bullet \tag{15}$$

The coefficients will vary from VOC to VOC. In general, the more complex the VOC, the more NO_2 that can be created on a per molecule basis.

The efficiency of equations 14 and 15 not only depend on the actual VOC reacting, but they also depend on the VOC/NO_x ratio. Fig. 1 shows a graph relating VOC and NO_x to the amount of ozone created. The solid curved lines represent the amount of ozone produced for a given mixture of VOC and NO_x. The relationship between NO_x, VOC, and ozone is clearly non-linear. The centers of most urban areas are VOC limited due to large volumes of traffic and commercial industry that produce large amounts of NO_x. Rural areas are almost always in the NO_x limited area of the graph. Note that for a given amount of VOC, ozone production will decrease if NO_x values get too high. The large amount of NO_x relative to VOC's permits the chemical scavenging of equation 3 to hamper the production of equations 14-15. As a result, urban centers generally have lower levels of ozone than the surrounding rural areas (although the actual values in urban centers can still exceed federal standards). Under a VOC limited scenario, reducing NO_x may actually lead to an *increase* in ozone levels (although, if the air parcel is then transported into a

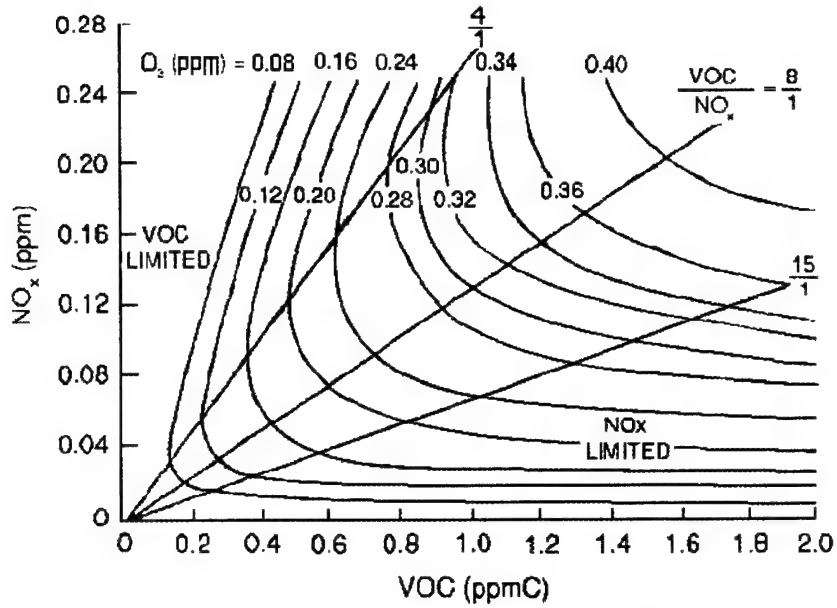


Fig. 1: Ozone isopleth diagram for various ratios of VOC's and NOx. [Adapted from NRC (1992)]

NO_x limited area, ozone values will decrease).

2.2. Literature Review

Ozone behavior in other cities and regions throughout the world has been extensively studied over the past 25 years in an effort to develop effective control strategies. A few of the regional studies have included the DFW area and will provide some insight, but most studies were from other areas. These studies are grouped into four categories: Spatial ozone behavior, temporal ozone behavior, relationships between ozone and meteorology, and the transportation of ozone and precursors.

2.2.1. Spatial Ozone Behavior

There are natural sources for both NO_x and VOC's, therefore some ozone is produced in the absence of anthropogenic activity. As discussed earlier, this natural ozone plays a key role in the oxidizing capacity of the troposphere through its relationship with the hydroxyl radical. However, observational evidence suggests that surface ozone levels have increased dramatically over the past century in many rural regions of the world (Bojkov, 1986; Janach, 1989; Crutzen, 1988; and Logan, 1985). This increase is thought to be anthropogenic in origin. Beyond having an effect on the health of plants and animals, rising values of ozone will also impact on tropospheric chemistry, and could also contribute to the greenhouse effect (IPCC, 1996).

Regional ozone levels are receiving increasing attention. Regional study groups are being formed to develop appropriate control strategies. In 1988 a

group of eight southeastern states in the US were chosen to comprise a regional study area called the Southern Oxidants Study (SOS) area. In 1993 the original states were expanded to include Texas and Louisiana. This study group found that ozone episodes in the South were decoupled from episodes in the North. In another study, Eder et al. (1993) performed a Rotated Principle Component Analysis (PCA) on ozone over the entire eastern half of the United States. This resulted in the identification of six regions or "influence regimes" whose ozone concentrations exhibit unique homogeneous characteristics. Texas and much of Louisiana were one of these regions, referred to by the authors as 'southwest'. Within this southwest region Houston has received the most attention in ozone research. However, ozone behavior here is strongly influenced by the local meteorology of the Gulf Coast region and may not be representative of behavior in other parts of the region. A previous PCA study by Cox and Clark (1981) concentrated on just the northeastern portion of the United States, but found similar bounded regions of independent ozone behavior. The results of these studies suggest that ozone in the DFW area may not behave in the same manner as the well-studied areas in the North.

Most of the published work has concentrated on urban scale ozone behavior. Works reviewed include Carroll et al. (1997), Karl (1980), Vukovich et al. (1979), Ludwig (1978), Burrows et al. (1995), Chu (1995), Eaton et al. (1979), and Altshuller (1988). While these studies were performed over different urban areas, all found the development of an 'urban plume' of ozone

and precursors, which generally emanates from major emission areas and is advected with the prevailing winds. The highest values of ozone are found in rural areas downwind of major emission areas and urban centers. Urban centers tend to display relatively low concentrations of ozone due to the greater chemical scavenging occurring near emission zones as discussed in the previous section.

2.2.2. Temporal Ozone Behavior

Studies of long-term, inter-annual, ozone behavior have been conducted to assess the effectiveness of control efforts. Most of these studies have reported mixed results. The NRC (1992) report states that meteorology must be removed from the ozone record in order to assess how precursor control strategies are affecting ozone statistics. Cox and Chu (1993) conducted such an analysis on 43 urban areas including Dallas. For Dallas they found a statistically significant downward trend in ozone exceedences from 1981-1991. A Texas Natural Resource Conservation Commission (TNRCC) in-house study using data from 1980-1996 also found a downward trend in Dallas (Dr. David Sullivan, TNRCC, personal communication). Fiore et al. (1998) also performed a trend analysis of many cities across the country. They found downward trends only in urban centers where the VOC reductions of the past decade have had an impact. At the heart of these trend analyses is the ability to remove the influence of meteorology. In the Cox and Chu (1993) study, the regression equation derived to remove the meteorology did not perform very

well in Dallas. The correlation between the regression model and observations when predicting the 95th percentile of daily maximum ozone was only 0.41. Only five of the 43 cities Cox and Chu considered had lower correlations. Ideally, one would want a better performance to ensure the observed trend is due only to changes in precursor levels. Interestingly, four of the five cities that performed worse than the DFW area were southern cities (Beaumont, El Paso, Miami, and Tampa). This poor performance in the southern cities may suggest a different relationship between meteorology and ozone than seen in the north.

A pronounced annual cycle is observed in maximum ozone values of urban areas. As a result, urban areas exhibit a high ozone 'season' during which most of their exceedences will occur. Vukovich (1997) decomposed five-year ozone time series for the eastern United States into mean, inter-annual, intra-annual, and synoptic components. He found that the annual cycle averaged 42ppb with a maximum in June and minimum in December as one would expect of a photochemical agent. He concluded that the annual cycle could contribute up to 20% of the daily observed maximum concentration.

Synoptic time scale (3-5 day) variations are perhaps the most studied of time scale variations. The NRC (1992) report states that high ozone days tend to occur sequentially. This behavior is often linked to the episodic nature of air masses, which move through the area. Ryan (1995) studied ozone behavior in the Baltimore and Washington D. C. area and found that 70% (159 out of 227 days) of ozone violation days occurred sequentially. Furthermore, 19 of the 20

most severe ozone days occurred as part of multi-day events. As a result of this behavior, moderate to strong correlation is often found between yesterday's and today's maximum ozone. To understand how yesterday's ozone impacts on today's requires discussion of the diurnal cycle within the Planetary Boundary Layer (PBL). Stull (1988) presented an idealized view of the PBL diurnal cycle. During the day, local area heating produces the so-called Convective Boundary Layer (CBL) through which air is relatively well mixed. This layer extends from the surface up to sometimes several thousand feet depending on the stability of the overlying air and the strength of the daytime heating. At night this boundary is split by radiational cooling into a lower stable Nocturnal Boundary Layer near the surface and an upper Residual Layer (RL). Mixing between these layers is effectively eliminated due to inversions formed by radiational cooling. On the following day, daytime heating destroys the boundary between the NBL and RL allowing the two air masses to mix freely once more. Neu et al. (1994) showed that while ozone in the NBL is being drawn down by surface deposition, ozone can be preserved overnight in the RL above the NBL. This ozone is then mixed down the following day enhancing surface ozone levels by 50-70%. Vukovich (1997) found that these synoptic variations could account for up to 60% of a daily maximum concentration leading him to conclude that episodic control strategies would be necessary to completely eliminate high ozone episodes.

Finally, surface ozone shows significant diurnal variations with minimums in the early morning hours around sunrise, and maximum in the early afternoon (NRC, 1992). The lack of photochemistry at night allows deposition and chemical scavenging to lower ozone levels significantly (values near zero are possible in urban areas where chemical scavenging is greater).

2.2.3. Relationships Between Ozone and Meteorology

The daily maximum ozone concentration is a combination of ozone precursors and meteorology. Robeson and Steyn (1990) demonstrated in a study conducted in British Columbia that statistical forecast techniques with both meteorology and ozone data were far superior to univariate models and persistence. Meteorology plays a significant role due to its influence on the chemistry of ozone formation. In general, warm temperatures, sunny skies, light winds, and restricted mixing heights are ideal to maximize ozone production. Warm temperatures are important to the reaction kinetics while the sunny skies are critical to effective photochemistry. Light winds and reduced mixing heights help to concentrate the precursors and prevent their dispersion. However, the specific blend of meteorology that maximizes ozone formation potential will vary from city to city, largely because the meteorology variables are heavily co-dependent and that co-dependency will change from location to location. In short, understanding an urban ozone problem requires knowledge of ozone behavior with synoptic weather patterns or with specific meteorological variables.

Studies correlating synoptic meteorological patterns with ozone behavior included Goldberg (1981), Zurita and Castro (1983), McKendry (1994), Eder et al. (1994), Prior et al. (1995), Davies et al. (1992), Comrie (1994), Comrie and Yarnal (1992), Hanna (1991), and O'Hare and Wilby (1995). A slowly moving or stagnate summertime anti-cyclone was the meteorological condition most condusive to the formation and accumulation of high ozone values. These systems generally displayed warm temperatures, light winds, a high percentage of sunshine, and high values of convective stability. Chameides and Cowling (1995) point out however, that mesoscale variations within these high pressure systems in the southern United States, especially concerning stability, makes the local meteorology important.

Studies correlating specific meteorological variables included: Rhodes et al. (1996), Ludwig (1978), Aron and Aron (1978), Lui et al. (1994), Hawke et al. (1983), Robeson and Steyn (1990), Feister and Balzer (1991), Prior et al. (1981), Eder et al. (1994), and Chu (1995). Temperature is often sited as the most highly correlated variable with daily maximum ozone. Prior et al. (1981) found an ozone-temperature correlation coefficient of 0.78. Clark and Karl (1982) looked at 27 stations in the Northeast US and found temperature the most highly correlated variable in most instances. Burrows et al. (1995) found similar results when studying cities in Canada. While often dominant, temperature is not the only meteorological variable found to have significant correlation with ozone. Other variables showing correlation in some cities

include: Surface wind speed and direction, dew point, relative humidity, pressure, upper level temperatures and winds, % sunshine, and mixing height. The Rhodes et al. (1996) study used 1990-1993 data from Texas cities to develop a regression equation to forecast daily maximum ozone during the summer of 1996. This study found the two meteorological variables most highly correlated with daily maximum ozone during 1996 in Dallas were maximum temperature (r=0.653) and percent of possible sunshine (r=0.514).

2.2.4. Transportation of Ozone and Precursors

Any local ozone control strategy must be able to distinguish between ozone produced in-situ and ozone transported into the area from other sources. Several studies along this line have been conducted. Prior et al. (1981) concluded that the highest ozone days in St. Louis were being enhanced by transport from the Ohio Valley. Altshuller (1986) reach similar results when he concluded that there was a tendency for the highest ozone values in St. Louis to be associated with advective conditions from the east. Karl (1978) examined high ozone days at the periphery sites around St. Louis using backward trajectories to determine if ozone was always a result of precursors from local emission areas. He found that emissions from other areas could be advected into the area. Burrows et al. (1995) reached a similar conclusion for the city of Montreal using the most frequently observed wind speed and direction over a 24hr period as a surrogate for transport direction. Hanna and Chang (1995) found that high ozone values near Lake Michigan

only occurred when trajectories carried air from high pollution sources. Comrie (1994) and Comrie and Yarnal (1992) demonstrate how the southwest flow on the west side of anticyclones transports ozone and precursors into the northeast portions of the United States. Eder et al. (1994) uses similar arguments to show that the east side of anticyclones can transport ozone and precursors into Birmingham, Alabama, from the north. Most recently, an air quality working group was formed known as the Ozone Transportation Assessment Group (OTAG). Their 1997 report (OTAG, 1997) concluded that transportation of ozone and precursors do impact ozone levels of other areas. This is especially true in the Ohio River Valley and along the northeast coastal area. OTAG also concluded that transportation scales in the south were shorter on average than in the north.

2.3. The Dallas-Fort Worth Precursor Overview

Any effort to describe ozone behavior in the DFW area requires at least a basic knowledge of the precursor environment around the DFW area. Both VOC's and NO_x have natural and anthropogenic sources. This section will present the anthropogenic source regions in an effort to identify the source area of the 'urban plume'. This information will be used to characterize the spatial behavior of ozone and to assess the influence of long range transport on the DFW area. Anthropogenic sources of VOC's and NO_x are generally broken into two categories: Point source and non-point source.

Point source emissions are those that occur at a fixed site. Most of these are utilities or industry. Fig. 2 shows a map of what is defined as the DFW area by the EPA with the percentage of VOC and NO_x point source emissions by county, relative to all of the counties in area. For VOC, clearly Dallas and Tarrant counties dominate. NO_x is slightly different. Ellis county produces the most with 22%, Dallas is next at 16%, and Hood county to the west produces 14%. For Ellis and Hood, NO_x production comes mostly from several utility plants. In the case of Dallas County, there are multiple sources.

Non-point sources are dominated by motor vehicles. A 1993 Texas Traffic Map places the heaviest motor vehicle activity in Dallas and Tarrant counties. Traffic volume is heaviest along the portion of the loop to the north of downtown Dallas. A 1995 Mobility 2010 Plan Update entitled: The Transportation Plan for North Central Texas, produced by the North Central Texas Council of Governments confirms that heaviest traffic congestion (and therefore the largest emissions) are found along the roads to the north of downtown Dallas (Fig. 3).

Combining the above information suggest that the strongest plume of precursors on any day probably emanates from Dallas and Tarrant counties.

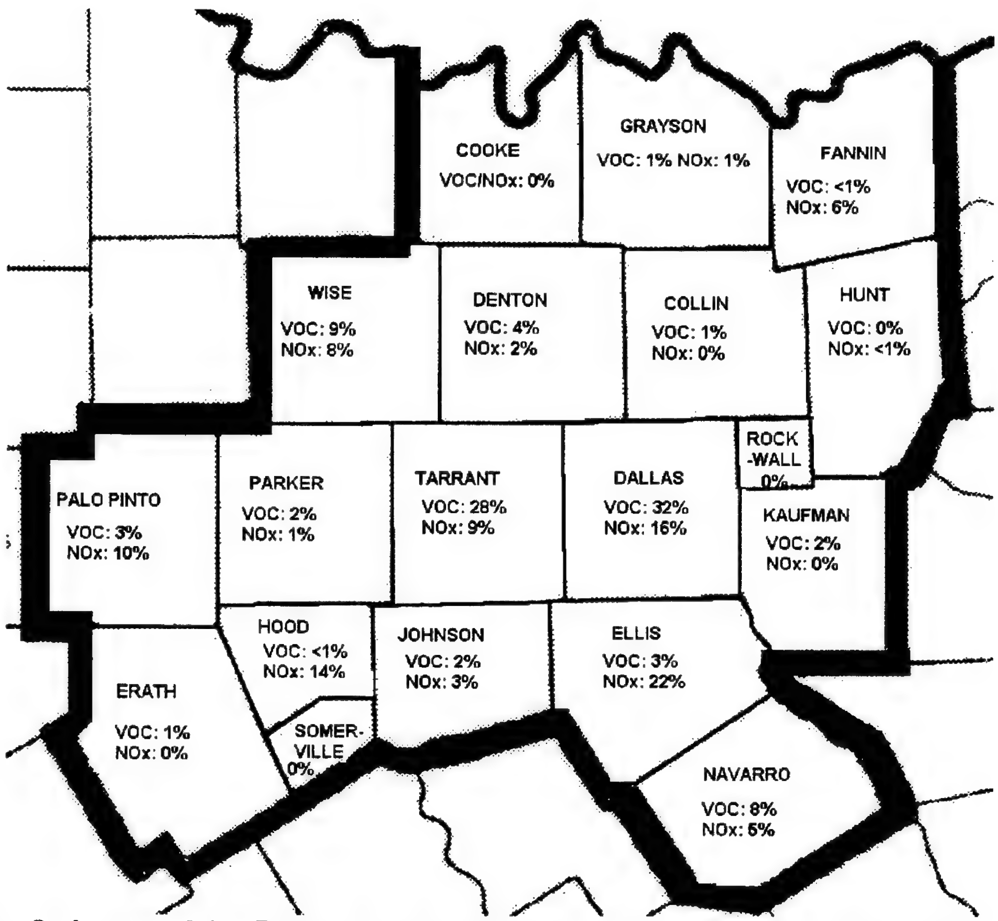


Fig. 2: A map of the Dallas-Fort Worth area showing anthropogenic point source emissions of VOC's and NOx by county. Percentages are relative based on the total point source emissions for all of the counties in this region. [Data obtained from the emissions inventory available on the TNRCC internet web site.]

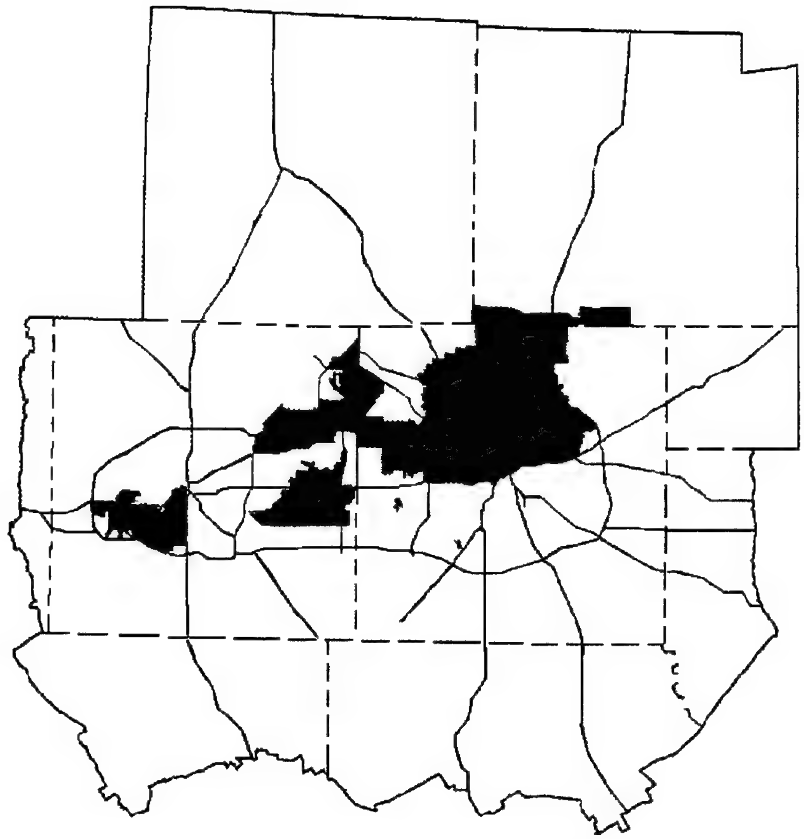


Fig. 3: A map of the Dallas-Fort Worth area depicting areas of congested traffic in 1990. Darkened areas represent congested traffic areas. [Adapted from the North Central Texas Council of Governments Regional Transportation Plan (1995).]

3. DATA AND METHODS OF ANALYSIS

3.1. Data

Surface ozone measurements have been made in the DFW area since 1973 and are available for download from the TNRCC internet web site. Surface meteorology has been measured at the DFW International Airport (situated midway between the cities of Dallas and Fort Worth) since its construction in 1974. Upper air data for the area was collected in Stephensville, TX, approximately 70 miles to the southwest of Fort Worth until mid-1994 when the site was moved to Fort Worth.

3.1.1. Ozone Data

Ozone data consists of hourly average readings. It is measured using an ultra-violet absorption technique and can be measured to parts per billion (ppb) accuracy. Data from 1978-1991 were rounded to parts per hundred million (pphm); data since has been reported in ppb. Although many studies look at days > 120 ppb, this study will use days > 124 ppb to stay consistent between rounded and non-rounded years. Although ozone monitors have operated in the DFW area since 1973, a questionable instrument calibration technique makes data prior to 1980 suspect (Dr. Dave Sullivan, personal communication; Mitchel et al., 1983). Therefore, only ozone data from 1980-1996 will be analyzed in this study. Table 1 presents information on the 23 different monitors that have operated at some time over the study period. Each has been numbered from 01 to 23 for ease of reference in this report. Only two sites (06 and 10) offer a continuous time series throughout the period. The number of monitors active at any one time has varied from 5-9. Fig. 4 is a map

Table 1: Current and historical ozone monitoring sites in the Dallas-Fort Worth area.

Site #	Site Name	AIRS #[1]	Latitude	Longitude	County	Report Period[2]	Total Days[3]	R, S, or U[4]
01	Arlington	484390005	32°39'50"N	97°06'00"W	Tarrant	01/80 - 06/81	515	Rural
02	Bonnieview	481130055	32°37'00"N	96°45'25"W	Dallas	04/82 - 07/94	4319	Rural / S
03	Colony	481210054	33°04'19"N	96°51'41"W	Denton	02/81 - Current	5634	Rural
04	Denton Aprt.	481210033	33°12'22"N	97°11'43"W	Denton	06/93 - Current	1270	Rural
05	Denton	481210002	33°11'59"N	97°11'37"W	Denton	05/92 - 10/92	180	Rural
06	Dallas North	481130045	32°55'35"N	96°48'28"W	Dallas	01/80 - Current	5962	S. Urban
07	Ennis	481390082	32°19'35"N	96°39'49"W	Ellis	03/91 - 10/91	241	Rural
08	Frisco	480850005	33°07'56"N	96°47'09"W	Collin	05/92 - Current	1632	S. Urban
09	FW Downtown	484391003	32°45'40"N	97°19'46"W	Tarrant	01/80 - 05/81	438	Urban
10	FW NW	484391002	32°48'19"N	97°21'26"W	Tarrant	01/80 - Current	5983	Urban
11	Hinton	481130069	32°49'10"N	96°51'40"W	Dallas	07/86 - 05/94 04/95 - Current	3478	Urban
12	Illinois[5]	481130052	32°43'10"N	96°53'24"W	Dallas	07/80 - 12/87	2521	S. Urban
13	Johnson Co.	482510002	32°23'13"N	97°24'12"W	Johnson	03/89 - 10/90	316	Rural
14	Keller	484392003	32°55'19"N	97°16'55"W	Tarrant	09/82 - Current	5042	S / Rural
15	McKinney	480850085	33°14'29"N	96°39'14"W	Collin	04/86 - 09/86	150	Rural
16	Mockingbird	481130044	32°49'10"N	96°51'40"W	Dallas	01/80 - 04/86	2204	Urban
17	M. Tower[6]	481390015	32°25'45"N	96°59'55"W	Ellis	07/96 - 09/96	77	Rural
18	N Tarrant	484392002	32°56'39"N	97°21'12"W	Tarrant	02/81 - 08/82	396	Rural
19	Parker Co.	483670080	32°45'40"N	97°49'55"W	Parker	06/88 - 09/88	110	Rural
20	Redbird Aprt.	481130087	32°40'40"N	96°52'29"W	Dallas	01/95 - Current	724	S. Urban
21	Rockwall Co.	483970081	32°56'35"N	96°23'10"W	Rockwall	06/88 - 09/88	121	S. Urban
22	Sunnyvale[5]	481131047	32°47'40"N	96°34'07"W	Dallas	4/80 - 10/81	227	Rural
23	Terrel	482570001	32°45'38"N	96°18'42"W	Kaufman	03/91 - 10/91	244	Rural

1. Aerometric Information Retrieval System (AIRS) is the ozone database maintained by the EPA.
2. Only dates between 1980-1996 were considered here. Many sites operated prior to 1980.
3. Total number of days the monitor operated between 1980-1996 for which data was available.
4. Rural, Sub-Urban, or Urban. Determined from TNRCC site surveys when available.
5. TNRCC Site Survey forms not available.
6. Operations at this site started again at the end of 1997. The site remains active today

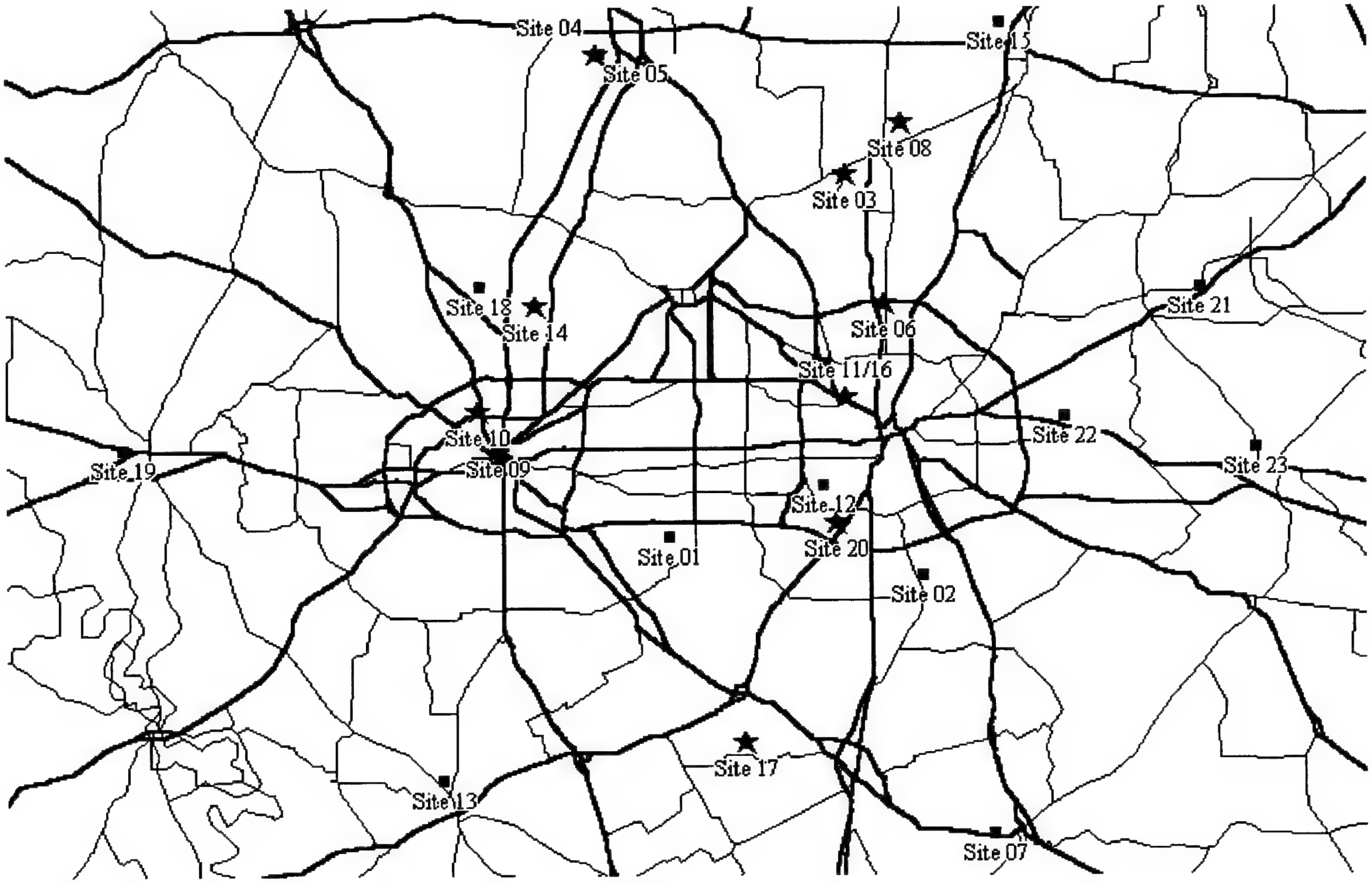


Fig. 4: Map displaying all current and historical ozone monitoring sites in the Dallas-Fort Worth area. Sites designated with stars are those active today.

displaying the locations of the sites. The sites designated with stars are those that are active today.

3.1.2. Meteorology Data

Surface meteorology data from the Dallas-Fort Worth International Airport was used to conduct the ozone-meteorology analysis. Data from 1980-1994 were obtained from the Office of the State Climatologist located at Texas A+M University. Data for 95-96 were not available in electronic format so analysis of ozone and meteorology relationships were conducted using data from 1980-1994. Data used included: Hourly measurements of temperature, pressure, wind, relative humidity, current weather, dew point, and sky cover.

Upper air meteorology data was obtained from the Air Force Combat Climatology Center (AFCCC) in Asheville, North Carolina. Again, only data from 1980-1994 was available in electronic format. Data was interpolated so that output is formatted every 500 feet. The closest Rawinsonde site to the DFW area during the study period was Stephensville, located approximately 70 miles to the southwest (This site was moved to Fort-Worth in 1994). The distance limited analysis possibilities, but relationships between ozone and the following fields were examined: Temperature, wind speed and direction below 5000 feet, and three convective indices.

3.2. Methods of Analysis

3.2.1. Ozone Climatology

The original data arrays for each station consisted of hourly average ozone readings. From these original files, other data arrays were created. A summary of these steps follows.

First an array consisting of the daily highest hourly average concentration over the entire area was created. This array was the primary one used to correlate and compare to meteorology variables. In addition, using this array, each day was averaged with itself over the 17-year time series to create a mean annual cycle of daily maximum ozone from 1980-1996. A three-day running mean was then performed to smooth the data for examination. The annual cycle was used to assess what dates were appropriate for the 'high ozone season' in the DFW area.

Although regulators are most interested in exceedence days, these days only make up a small percentage of the total days. From a statistical viewpoint more data is desirable. So for the purposes of this study, in addition to being interested in exceedence days, a high ozone day will be defined as a day in which one or more active sensors recorded ozone readings greater than 104 ppb. These days were separated from the original data into an array so that high ozone day behavior could be examined spatially and temporally. A 'high ozone season' was then determined by examining the three-day mean annual cycle and temporal behavior of high ozone days. All further analysis was limited to this season.

Specific station behavior was also examined. The likelihood of a station to record the maximum for the city was examined by computing the number of days the site recorded the city maximum (ties included) versus the number of days that site was active. The same exercise was performed on the high ozone data set.

Average diurnal cycles were also computed for each station over the lifetime of the station. Three years were then selected (1980, 1988, and 1996),

based on the spatial arrangement of stations, and diurnal averages were calculated to facilitate comparisons between stations.

3.2.2. Ozone - Meteorology Relationships

Relationships between surface and upper air variables were examined using a combination of the Pearson correlation and scatterplots. Meteorological variables selected were those that most often appeared in other studies. They included: Temperature, pressure, wind speed, relative humidity, cloud cover, dew point, and 1000-5000 ft temperatures and wind direction. Three stability indices (K-Index, Total Totals, and Sweat Index) were also considered in hopes of using them as a proxy for convective venting or mixing height. The K-Index is a convective coverage index while the Total Totals and Sweat Index provide information on the potential of severe weather. Effort was made to include only those variables that were routinely measured and forecasted, or at least easily calculated. For each variable selected, several variations were correlated against today's maximum ozone. For example, 24hr maximum temperature, 12L temperature, 15L temperature, and 18L temperature were all correlated against maximum ozone. From these one was selected to undergo further study, usually it was the one that correlated most highly, but some consideration was given to the practical usefulness of the selected variable. (For instance, the 15L temperature showed a slightly better correlation with ozone than the 24-hour maximum temperature, but the maximum temperature was chosen since the difference was not that great and operational forecasters most often consider the maximum temperature.)

Once a representative variable from each type was chosen, a scatterplot matrix was constructed in order to examine both linear and non-linear

relationships between ozone and the meteorological variables, plus among the meteorological variables themselves. For each variable, bounds were determined that highlighted the conditions necessary to achieve an ozone exceedence. Data was then re-examined by month to determine if variations in relationships existed within the season.

Conditional Climatology (CC) tables were then constructed as a tool to examine which combinations of variables were most likely to lead to an exceedence. The first step in creating the tables was to remove all days on which meteorological variables failed to fall into the bounds determined in the above analysis. With the remaining days, scatterplots were examined to determine which variables displayed the strongest relationship with ozone. Each selected variable was then broken into a finite number of categories, again based on the scatterplots. Non-meteorological categories such as yesterday's ozone and directional network biases were also considered. Each day was then classified as some combination of categories. Days with the same combination of categories were combined, and the pattern of ozone in each category combination was examined. Ideally, certain combinations of factors will be conducive to high ozone formation, while others will not be. The advantage of such a procedure is that it makes no underling assumptions about the data. The major disadvantage with this procedure is that it is very data hungry. Care must be taken to minimize the number of categories and thus keep the data numbers in each combination of categories reasonable.

3.2.3. Ozone and Precursor Transport

Transport both within and from without the DFW area was examined. Transport within the domain was considered to assess the siting of ozone

monitors in the DFW area. The technique was taken from Chu (1995). The windrose from all days is compared with one on only those days conducive to ozone development. Wind roses in table format were created for this study.

The potential for transport of ozone and precursors from outside the DFW area was assessed by examining the upwind vs. downwind average diurnal behavior of sites around the periphery of the DFW area. If no long-range transport component exists, these monitors should show high ozone values only when wind flow is from the metro-plex. This assumes that the only significant source of ozone precursors within the DFW area originates from the metro-plex area.

4. RESULTS AND DISCUSSION

4.1. Ozone Climatology

One of the goals of this research was to examine the behavior of ozone in and around the DFW area. Both spatial and temporal patterns and variations were examined. Special attention was paid to behavior at high ozone values (>104 ppb).

4.1.1. Temporal Ozone Behavior

Fig. 5 shows a boxplot of daily area wide maximum ozone readings from 15 Apr - 15 Oct over the time period of 1980-1996. Boxplot values (from top to bottom) are maximum reading, 90th percentile, 75th percentile, average (dot), median, 25th percentile, 10th percentile, and the minimum reading. The DFW area has exceeded the NAAQS in every year of the study period. Inter-annual variation is obvious within the data set, more so in the upper percentiles than in the lower percentiles. Changes in emissions and year to year variation in meteorology are the factors accounting for most of the variation. Separating the two factors is very important in order to assess the effectiveness of attempts to come into compliance with the NAAQS. For example, the upper percentiles show an encouraging decrease from 1988-1993. It would be great to say that efforts to reduce ozone are working; however, the long-term trend due to emission changes can only be examined if the meteorology is somehow normalized. This requires knowledge of the relationship between meteorology and ozone, a main goal in this study.

Daily maximum ozone readings exhibit a considerable annual cycle. Fig. 6 is a plot of the mean annual cycle for the area one-hour daily maximum from 1980-1996. A three-day running mean was computed to smooth the data

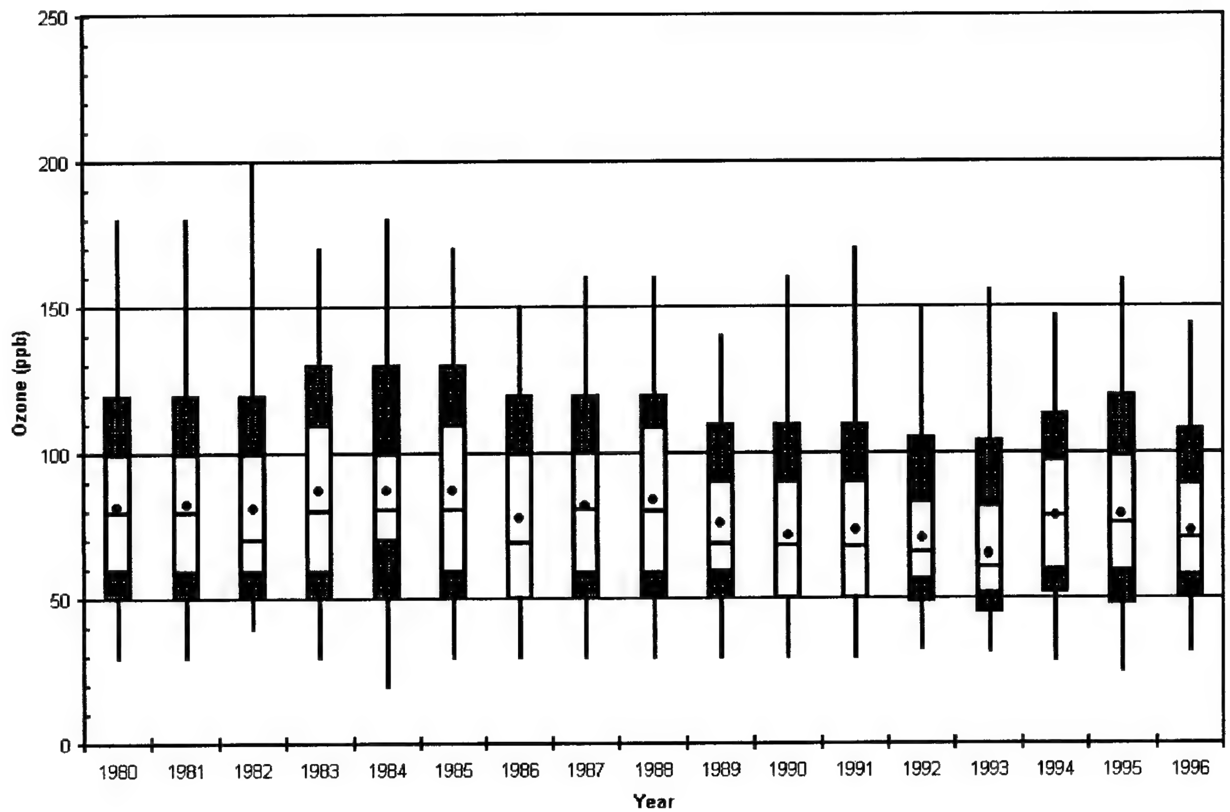


Fig. 5: Boxplot of daily area wide maximum ozone readings, 16 Apr - 15 Oct. Boxplot values from top to bottom are maximum reading, 90th percentile, 75th percentile, average (dot), median, 25th percentile, 10th percentile, and the minimum reading.

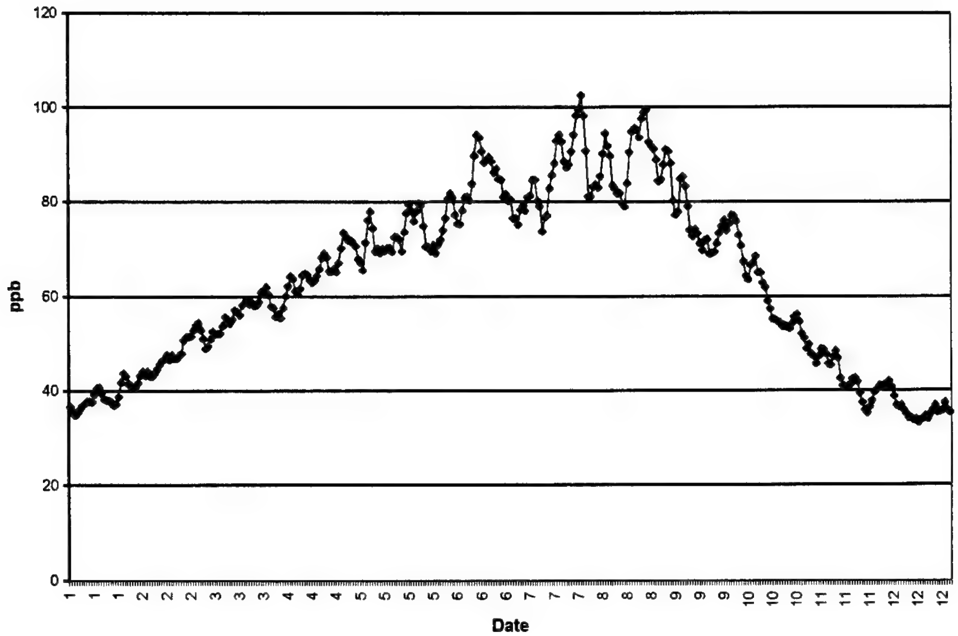


Fig. 6: Mean annual cycle for the area one-hour daily maximum ozone concentration.

slightly. A gradual increase during the spring, a broad maximum from the later half of July through August, and then a relatively rapid decline in the fall characterize the curve. This cycle is largely due to the influence of the astronomical and meteorological annual cycles. Ozone production is tied to solar intensity and is influenced by meteorology. The solar and meteorological summer lag each other producing the slow spring increase and rapid fall decrease. Overall, this cycle points to the presence of a high ozone 'season' during which most exceedences occur. The annual average of this cycle is 63 ppb. One way to define the high ozone season is to identify when the cycle is above the mean. For the DFW area this extends from mid April through mid October. Interest in ozone is usually centered on the high ozone days. Logically, any high ozone season should represent the vast majority of these days. Fig. 7 presents the percentage of days per month ozone highs exceeded 104 ppb (Fig. 7a) and 124 ppb (Fig. 7b). Clearly the months of June through September stand out. Looking at Fig 7b shows that all of the DFW exceedences have occurred between 16 Apr and 15 Oct. Given that this correlates well with the time period that the annual cycle exceeds the annual average, 16 Apr - 15 Oct will be defined as the high ozone season and all further analysis will be limited to this time period. The longer summer of the southern States results in a longer time period of potential high ozone.

Fig. 8 is a box plot of daily ozone maximums for this high ozone season. Values reported are the same as Fig 5. The annual cycle is clearly evident in

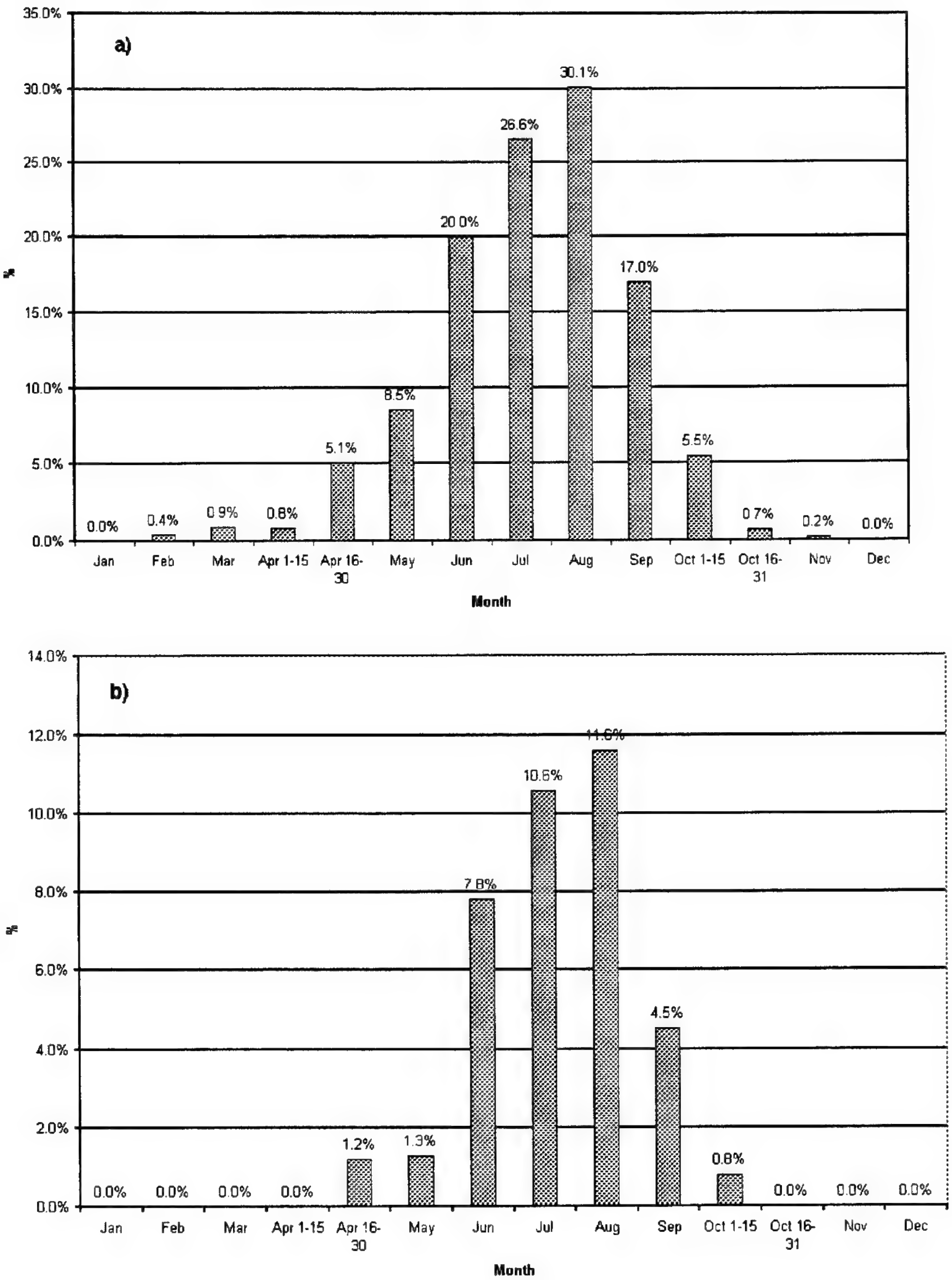


Fig. 7: Percentage of days DFW area ozone maximum exceeded a) 104 ppb and b) 124 ppb, broken out by month.

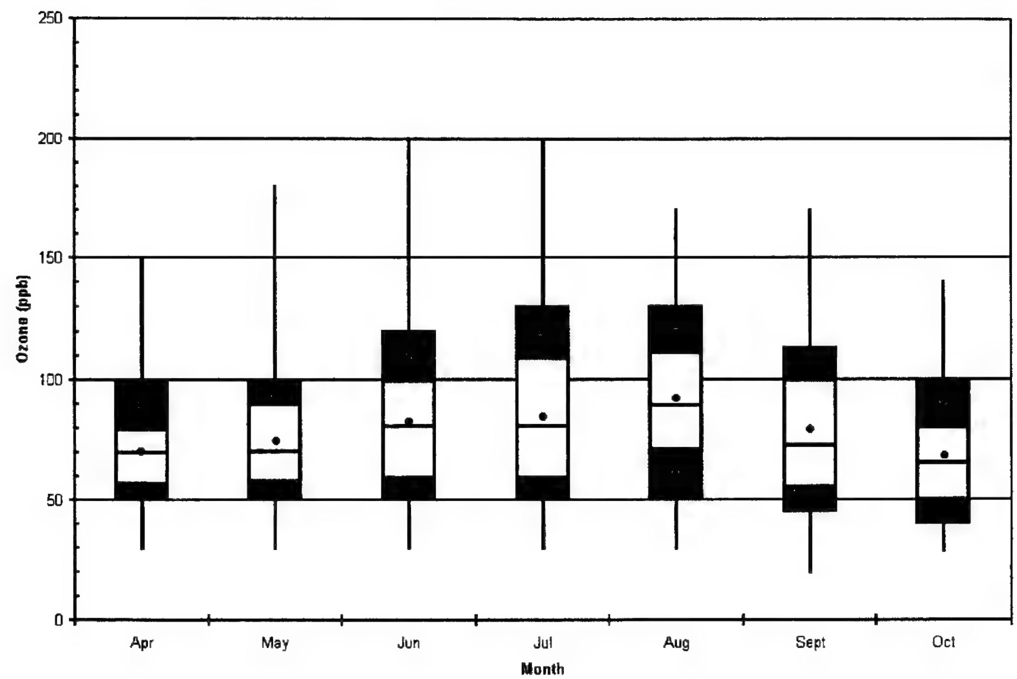


Fig. 8: As in Fig. 5 except boxplots are monthly.

the behavior of the upper percentiles, but is absent from the lower ones. The averages exceed the median because of the extreme values in the upper percentiles. The variance clearly increases in the middle of the summer. Overall, Fig. 8 suggests that ozone behavior will vary within the ozone season. This study will therefore examine ozone behavior within the season in addition to the season as a whole.

Next consider the episodic nature of ozone on synoptic time scales. Data similar to Ryan's (1995) study in Baltimore were calculated for the DFW area. The results from the DFW area show only 40% (80 of 198 days) of exceedence days occurred sequentially, and only 7 of the 14 most severe ozone days occurred as part of multi-day events. This is significantly lower than Ryan's 70% and 19 out of 20. However, to conclude that ozone behavior in the DFW area is non-episodic would be incorrect. The difference between the two cities is found in the severity of the ozone problems in each location. Baltimore exceeds the NAAQS on a much more regular basis than the DFW area. If the DFW area data is re-examined looking at days with ozone above 104 ppb then you find that 70% (393 of 560 days) occurred sequentially. Furthermore, 81% (160 of the 198 days) of exceedence days occurred within multi-day 105 ppb events. Ozone behavior in the DFW area is episodic in nature, consistent with findings from other cities. Table 2 presents statistics on the behavior of singular vs. multi-day 105 ppb events over the ozone season. Once again, the behavior over the season is not uniform. There is a

Table 2: Behavior of days with maximum ozone > 104 ppb over the season.

	Apr	May	Jun	Jul	Aug	Sept	Oct	All
# Days Ozone >104ppb Multi and Single Day	13	45	102	140	159	87	14	560
% of >104ppb Days Occurring Sequentially	38%	47%	65%	79%	82%	57%	71%	70%
Avg Length of Multi-Day Events	2.5	2.6	2.8	3.3	3.5	2.6	2.5	3.1
Median Length of Multi-Day Events	2.5	2	2	3	3	2	2	3

greater likelihood of multi-day 105 ppb events in the middle of the season than at either end, and these events are longer in duration.

Another way to view this episodic nature of ozone is through the correlation of yesterday's maximum ozone with today's maximum. This variable will capture the episodic nature for both anomalously high and low ozone behavior. In regression analysis performed on ozone in many cities throughout the world, yesterday's maximum ozone is often found to be one of the most powerful predictors of today's maximum ozone. Table 3 and Fig. 9 present correlation information of yesterday's ozone throughout the season based on the area wide maximum and the area wide average (domain) maximum. By averaging the daily maximum recorded at each site for a given day, you minimize the influence of emission variations throughout the domain and instead emphasize the larger scale production capability of the air mass. The correlation coefficient of the domain-averaged ozone maximum is nearly 0.6 suggesting that about 36% of the variance in today's maximum ozone are explained by yesterday's ozone (YOZ). Clearly July is the most persistent month, but variation in the coefficient over the season is not great. The correlation and thus the episodic nature of the ozone maximum does not seem to vary in a consistent manner throughout the season. So while the highest ozone episodes show a seasonal variation (Fig. 8), overall ozone episode behavior is consistent throughout the season.

Table 3: Average daily area and domain maximum ozone with correlations between yesterday's and today's maximum ozone.

	Apr	May	Jun	Jul	Aug	Sept	Oct	All
Average Daily Maximum Ozone (Area Maximum)	70.1	73.6	81.1	84.2	90.1	77.0	68.1	79.2
Average Daily Maximum Ozone (Area Average)	56.4	58.9	63.2	63.5	68.4	60.0	55.1	61.9
Correlation of Yesterday's Area Maximum to Today's	0.43	0.47	0.43	0.59	0.52	0.47	0.60	0.55
Correlation of Yesterday's Area Average to Today's	0.53	0.58	0.51	0.64	0.59	0.55	0.66	0.60

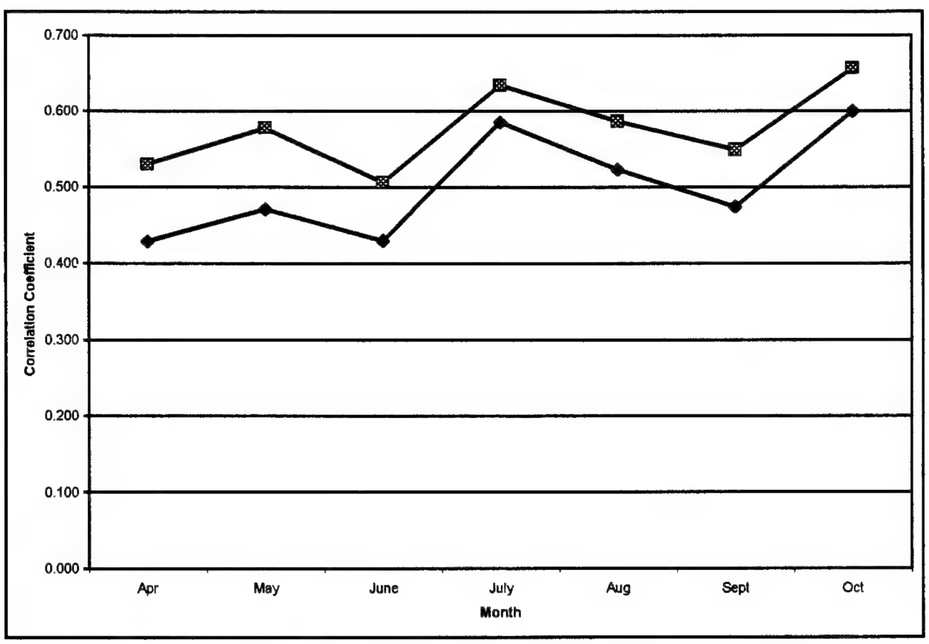


Fig. 9: Correlation coefficient between yesterday's and today's domain averaged maximum ozone (squares) and area wide maximum ozone (diamonds).

In section 2.2.2. the mechanism of how yesterday's ozone impacts today's was outlined. Here a simple experiment was performed in an effort to expose the effects of the RL on ozone development in the DFW area. Data from stations 06, 10, 11, and 14 were used to build two data series. In one were days that had ozone values at or above 80 ppb where the day prior had ozone values in excess of 100 ppb, and in the other were days with ozone values at or above 80 ppb where the previous day's ozone was at or below 50 ppb. Average hourly rates of change in ozone production were then calculated for each scenario at each station. The results are presented in Fig. 10. Clearly days with high ozone on the day prior have a much greater increase in morning ozone values. This is the effect of the RL ozone being mixed down. Also interesting are the higher afternoon production values for those days without high ozone on the previous day. The impact of high YOZ allows ozone to reach or exceed 80 ppb with less dependence on afternoon production.

In summary, the DFW area experiences ozone variations on a broad range of temporal scales. Daily maximum ozone behavior showed considerable variation from year to year. There is some evidence of declining ozone over the time period, but any serious analysis must attempt to normalize meteorological variations before drawing any definite conclusions. The pronounced annual cycle permits the defining of a high 'ozone season' during which most of the high ozone events will occur. The logical choice for the DFW area is 16 Apr - 15 Oct. All further analysis will be limited to this time period. Within this period, ozone still displays noticeable seasonality, thus some of the ozone behavior will be examined by month in addition to the period as a whole. At the synoptic time scale, ozone behavior was shown to

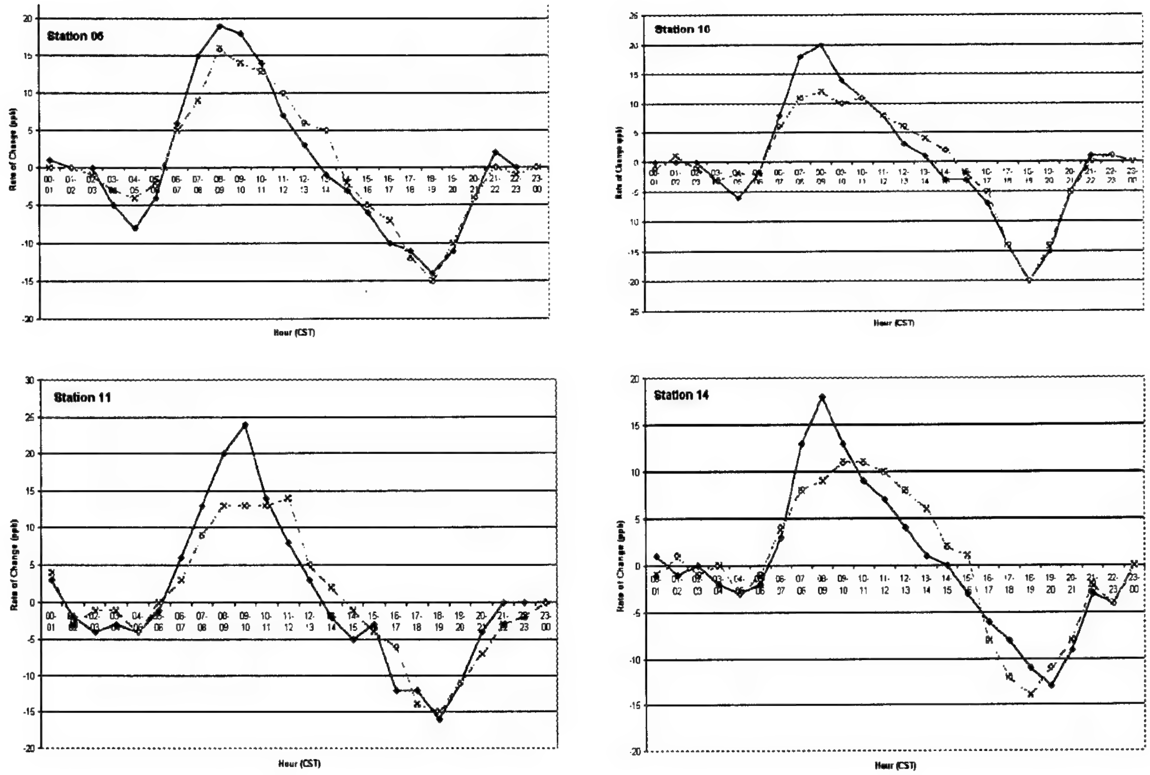


Fig. 10: Average rate of change of ozone on days with maximum > 80 ppb when previous day was > 104 ppb (solid curve) versus previous day < 51 ppb (dashed curve) for four different DFW stations.

be episodic. Correlation with yesterday's ozone showed a moderate (approximately 0.6) with today's.

4.1.2. Spatial Ozone Behavior

Section 2.2.1. discussed how ozone will vary over several space scales from global to urban. This section will concentrate on just the urban scale variations seen in the DFW area. The effects of changing chemistry and prevailing winds will combine to create differences in ozone behavior from the urban areas to the rural ones, and from one sector of the area to another. Section 2.3 concluded that the urban plume would emanate from the DFW metro-plex area. This plume would be expected to then track with the prevailing winds.

One of the most significant challenges to studying spatial ozone behavior in the DFW area has been the lack of a stable and consistent monitoring network. The periods 1983-1985, 1989-1990, and 1992-1994 were the only consecutive years with the same network configuration. Furthermore, the central and northern portions of the area have been sampled far more consistently, both spatially and temporally, than areas to the south, east, or west. Despite the inconsistent monitoring network, general behavior patterns should be observable.

Fig. 11 is a graph showing the likelihood of a particular station to record the daily maximum ozone reading for the area during its operating lifetime. Stations have been classified by what sector of the area they were in relative to the DFW metro-plex. Central stations are those placed within the dumbbell shaped 'beltway' surrounding the DFW metro-plex (see Fig. 4 for a map with the beltway). Again most of these sites operated at different time periods, so

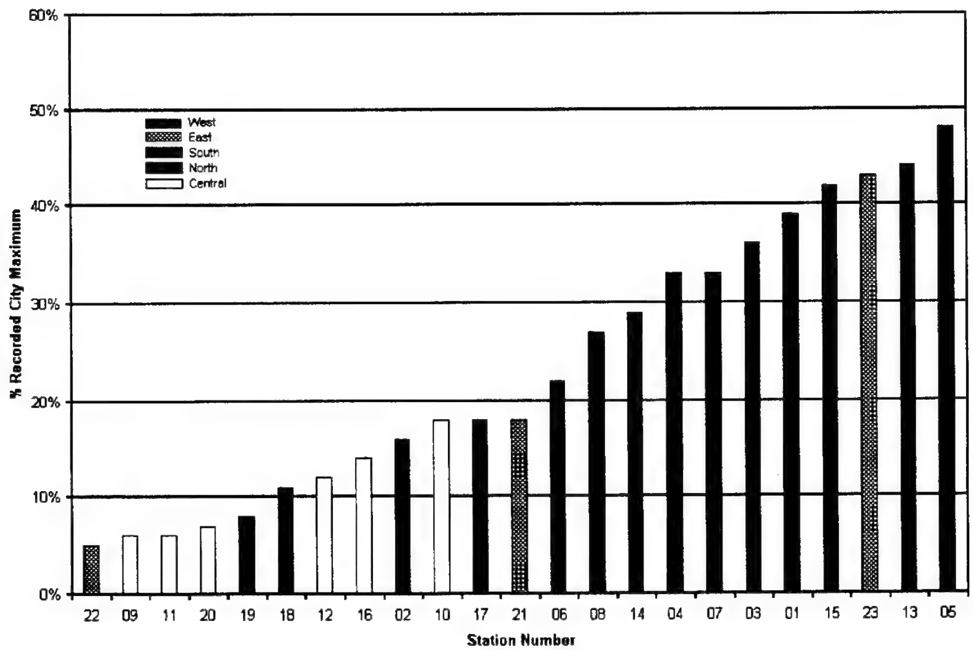


Fig. 11: Percentage of time a particular station recorded the maximum ozone for the DFW area. Stations are highlighted by city sector.

station to station comparisons are not warranted, but some generalities can be made. Sites located in the central region were less likely to record the area daily maximum than sites located outside the central area. Also, there is a rough relationship between likelihood to record the area maximum and distance from the central urban area. Among the ten stations most likely to record the area maximum, only station 01 is not among the most distant.

To facilitate direct station comparisons, it will be necessary to examine stations active over the same time period so that each were operating under the same emissions and meteorological background. Here average diurnal behavior will be examined so that differences in all aspects of behavior can be discussed.

Fig. 12 shows the average diurnal curves from four stations during the 1980 season. The southern site is station 01, downtown is station 09, east is station 22, and north is station 06. The downtown and northern sites are classified as urban while the remaining two are rural. In the morning, the northern and downtown sites have much lower ozone readings than the eastern or southern sites. This fits nicely with expectations of urban versus rural behavior as the high emissions environment of the urban areas titrates ozone via equation 3. Morning rates of change in ozone are much greater at the urban sites. This could be the result of the photolysis of overnight precursors from local emission areas at the urban sites, a resource that the rural sites would not have access to until later in the day when air begins to circulate emissions more widely. As afternoon begins ozone values at the urban sites level off and begin to decline in the afternoon while the rural sites don't peak until late in the afternoon. This can be attributed to the afternoon

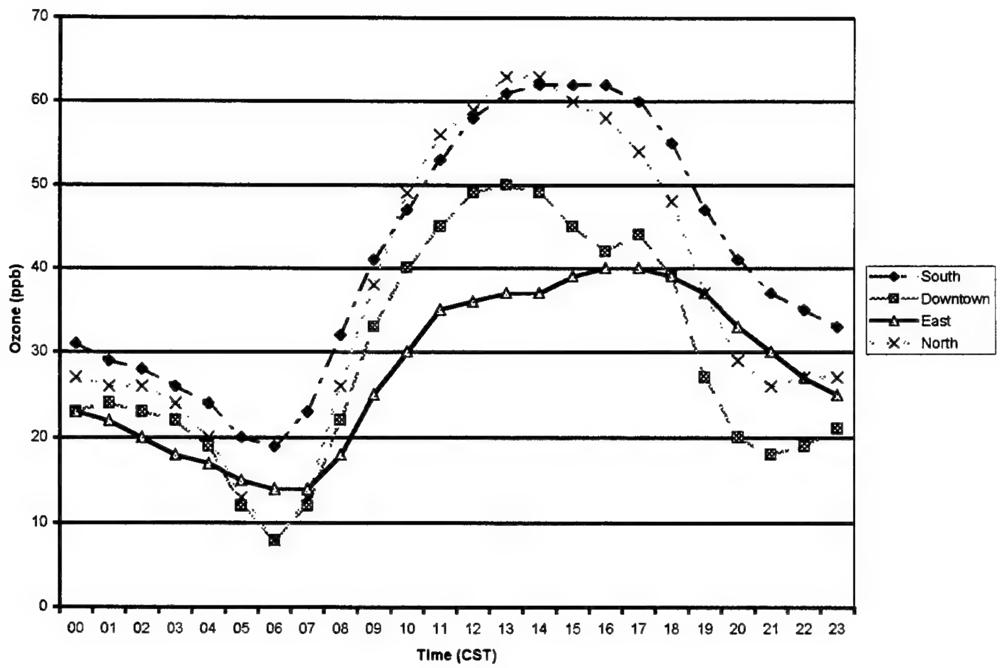


Fig. 12: Average diurnal curves from four stations in the DFW area during the 1980 season. South is station 01, downtown is station 09, east is station 22, and north is station 06.

rush hour traffic, which provide a quick surge of NO leading to ozone titration in the urban areas. Transportation of the urban plume likely accounts for the difference in behavior between the northern, eastern, and southern sites. The table top shape of the afternoon curve at the eastern site suggests that the urban plume was not often advected east of the city, while sites to the north and south clearly show an impact from the plume.

Fig. 13 shows the diurnal curves from 1988 (only June through September was used). Here we have rural sites from all major directions around the DFW metro-plex, plus a downtown urban site. West is station 19, east is station 21, downtown is station 11, north is station 03 and south is station 02. Again the downtown urban site has lower morning values and peaks earliest of the sites. The sites to the east, south, and west all plateau during the afternoon while the northerly site shows a more rounded shape with much higher values. This would suggest the greatest plume impact in the northerly sector. The differences in ozone levels among the east, south, and west could be a function of how often precursor plumes impacted the areas.

Fig. 14 displays data from 1996 (only July through September) representing a cross section from south to north through the DFW area. Stations 03 and 04 are north, with station 04 the northern most. Station 11 is downtown. Stations 17 and 20 are to the south with station 17 the southern most. Areas to the north display higher average ozone than areas to the south, and ozone values generally increase with increasing distance from the urban center. This pattern is just what one would expect of an area with a prevailing southerly wind pushing urban plumes to the north of an urban area.

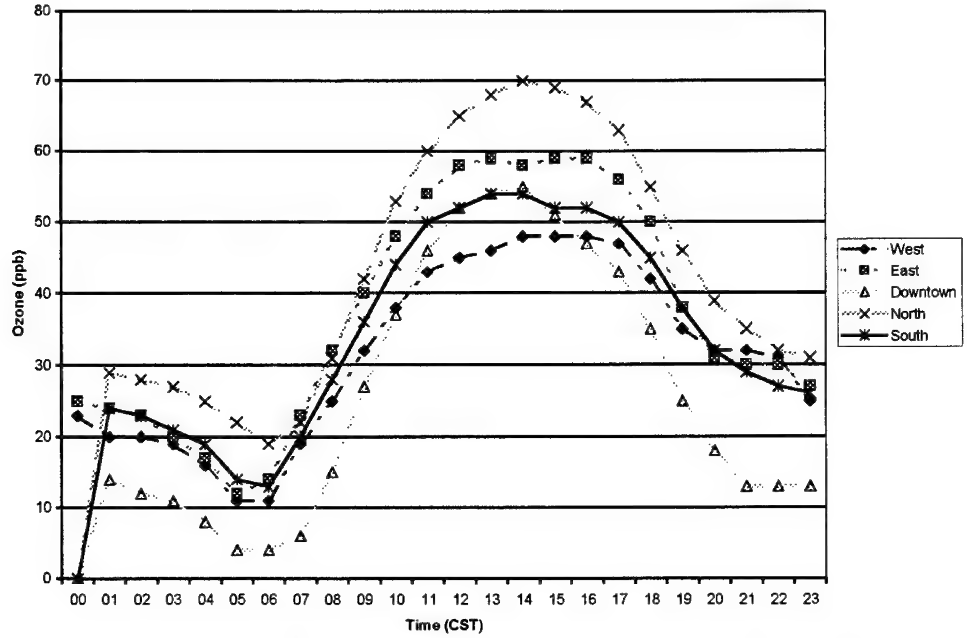


Fig. 13: As in Fig. 12 except curves are for 1988. Here, west is station 19, east is station 21, downtown is station 11, north is station 03, and south is station 02.

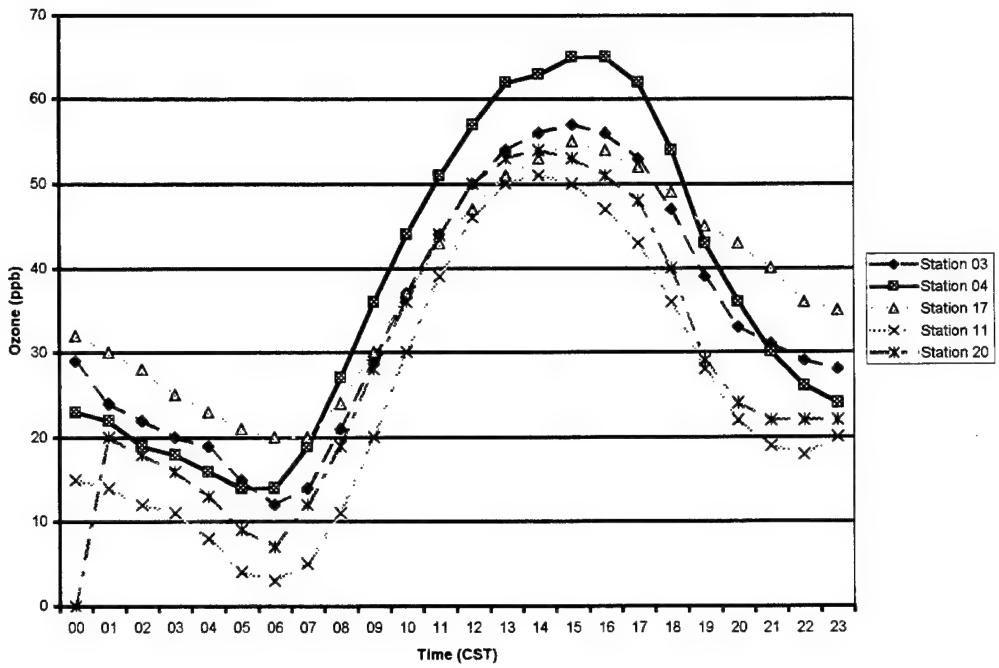


Fig. 14: As in Fig. 12 except curves are for 1996. Cross-section stations are identified in the legend.

These snapshots of different years suggest that the urban areas of the DFW metro-plex behave in a manner typical of a high emission source area with low morning readings, early afternoon ozone peaks, and overall lower average ozone maximums. Rural areas to the north of the metro-plex display the highest ozone readings and show evidence of frequent impact from an urban plume, while areas east, west, and south show overall lower values with less frequent plume impact.

High ozone days are generally of greater interest than others are so their spatial variations will also be considered. Fig. 15a shows the percent of days that a particular site had an ozone value greater than 104 ppb. In general, sites to the north were more likely to see these high values than sites located elsewhere. This is in line with what was found in the preceding paragraphs. Fig. 15b answers the following question: When a site recorded a value greater than 104 ppb, how often did that site also record the maximum for the network. In general two conclusions are possible. First, even when central areas are recording high ozone, ozone values are often higher in other parts of the area. Specifically, stations furthest from the metro-plex were the most likely to have high readings. Comparing station 16 between Fig. 15a and 15b illustrates this nicely. Site 16 was one of the most likely candidates for ozone readings above 104 ppb, but when it did, it usually was not the worse reading in the DFW area. The second conclusion from this figure is that high ozone on a particular day tends to be orientated in a specific direction. Generally, there was only one sensor operating in the east, west, and south at any one time. Whenever ozone values were high at these stations, it was generally the

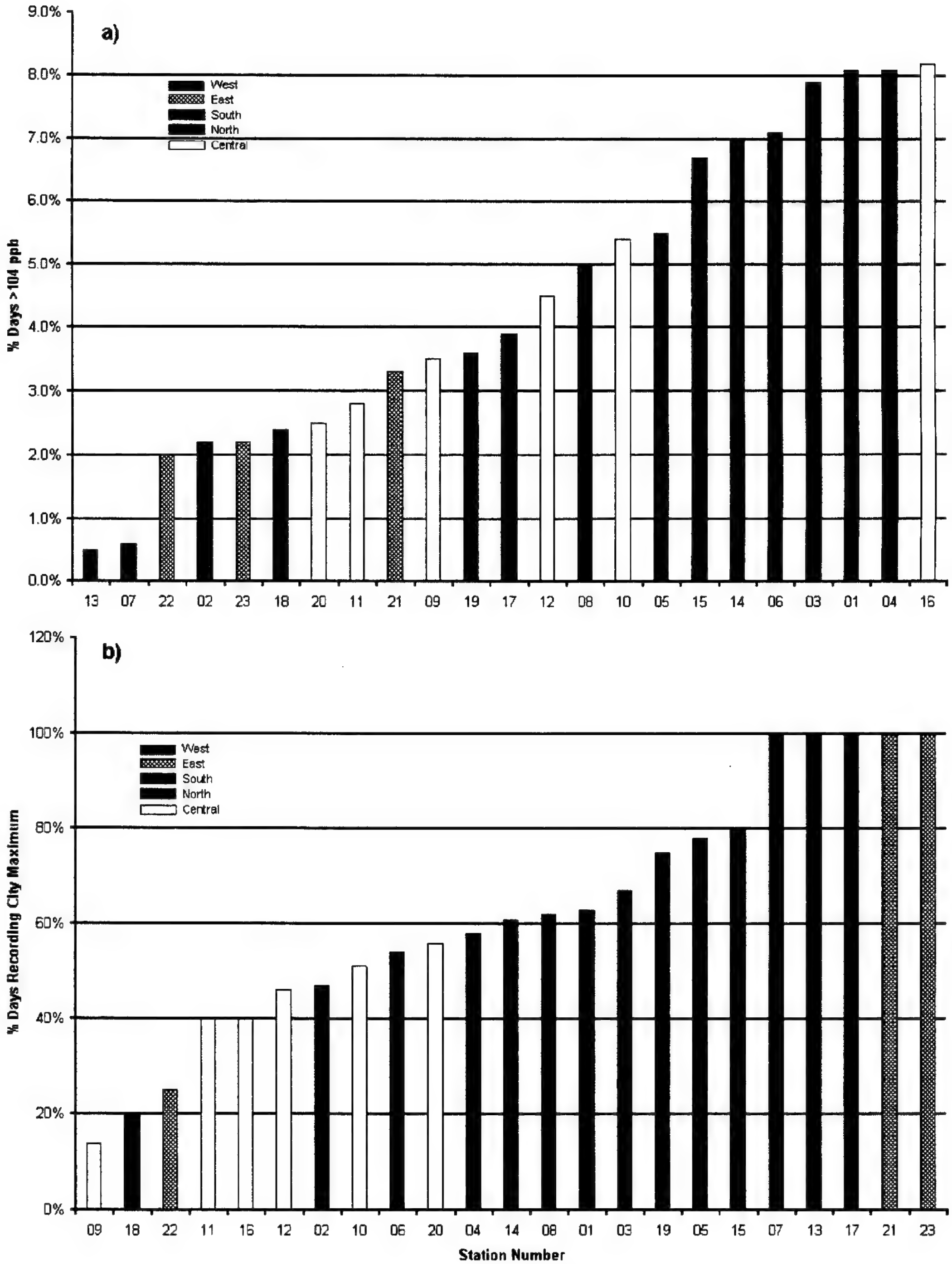


Fig. 15: a) Percent likelihood for a particular station to exceed 104 ppb. Stations are coded by sector relative to the DFW metro-plex. b) Percent of days that station recorded the maximum for the DFW area when ozone at that station exceeded 104 ppb.

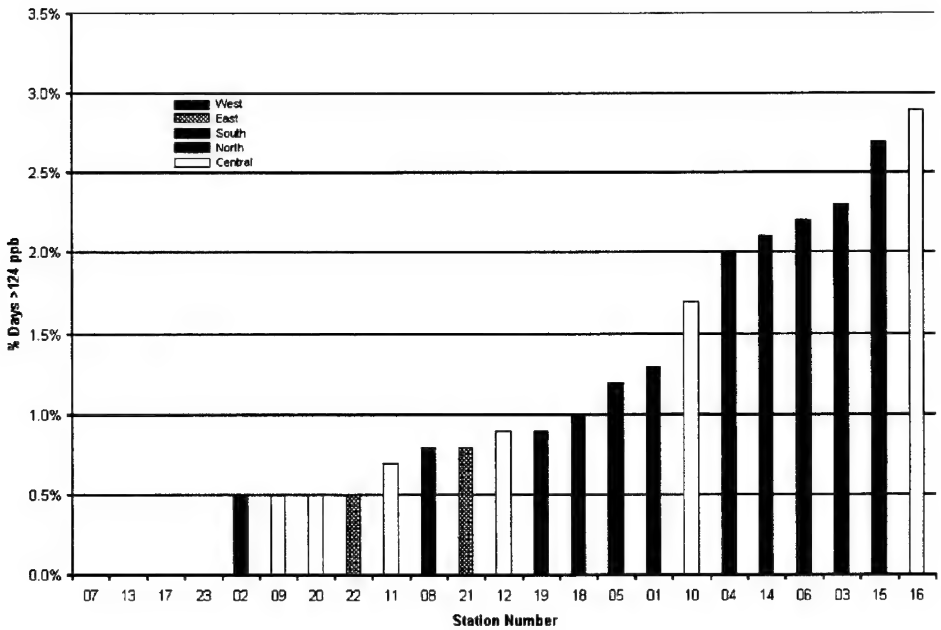


Fig. 16: Percent likelihood for a particular station to exceed 124 ppb. Stations are coded by sector relative to the DFW metro-plex.

highest reading in the entire DFW area. This fits with a precursor plume projected out from the DFW metro-plex with the prevailing wind for that day. For example, If the plume moves to the east, the sensors in the east record the highest values for that day. Fig. 16 shows the percent of days with an exceedence for each station over its lifetime. Clearly, northerly areas are, overall, more likely to record an exceedence. Note that several southern sites have never recorded an exceedence. The dominance of the northern stations for exceedences is interesting and could be the result of meteorology, transportation, or network configuration biases. In the coming discussion, we will see that it is likely a combination of all three.

4.2. Relationship Between Ozone and Meteorology

The poor performance of the model developed by Cox and Chu (1993) relating ozone to meteorology in the DFW area suggests that the relationship may be more complex or at least different than in many other areas. The first section will explore which surface and upper air meteorological variables show the clearest relationship to ozone. Then in the next section, Conditional Climatology Tables (CC Tables) will be used as a tool to explore what combinations of variables are most conducive to high ozone values.

4.2.1. Basic Ozone-Meteorology Relationships

The linear relationship of each meteorological variable was tested by calculating the Pearson correlation coefficient between maximum daily ozone and that variable (wind direction was not correlated, it will be considered in the

next section). Table 4 presents the coefficients for each variable considered. Different iterations of each variable were considered to see which showed the best relationship. Clearly none of the variables show a strong linear relationship with ozone. Compared with other studies, this is somewhat surprising, and is probably part of the reason for the poor performance of the Cox and Chu (1993) model. The lack of a linear relationship does not mean that the meteorological controls on ozone are different in the DFW area, rather it implies that the relationship between the meteorological variables is different.

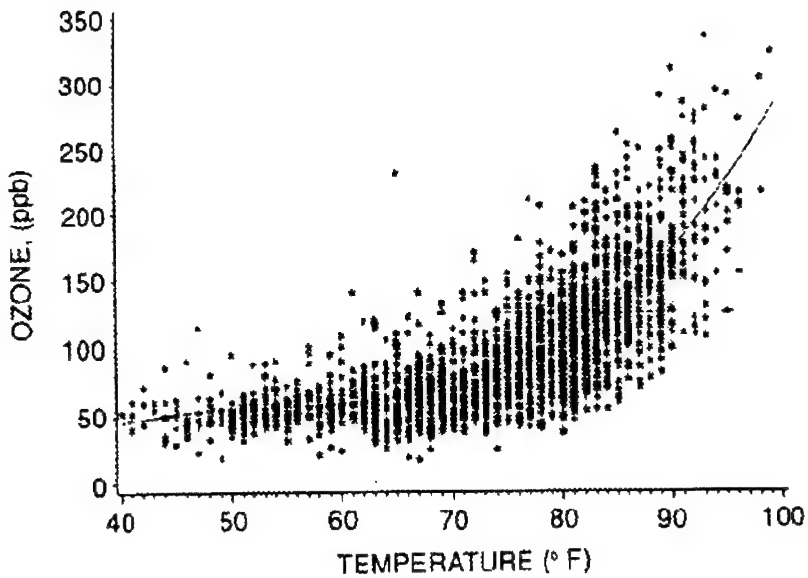
To examine this further, one iteration from each variable was selected (highlighted in bold in table 4) to examine further. In most instances, the variable with the highest correlation was chosen. In the case of temperature, maximum temperature was selected since none of the variables differed significantly and maximum temperature has been selected in many other studies. The 09-18L cloud cover was selected to remain consistent with the averaging time of the other variables. The 12Z sounding variables were selected to see if morning observations could play a predictive role. A scatterplot matrix relating the selected meteorological variables to ozone and each other was then constructed.

The lack of correlation with temperature offered the greatest initial surprise given the high degree of linear relationship quoted in many other studies outlined in section 2.2.3. Fig. 17 compares a scatterplot of temperature vs. ozone for the DFW area with one from Connecticut. While both imply that high

Table 4: Pearson correlation coefficients versus maximum daily ozone.

Temperature:	
versus Max Temp	**0.38**
versus ln(Mx Temp)	0.38
versus 12L Temp	0.38
versus 15L Temp	0.40
versus 18L Temp	0.37
Pressure:	
versus Max Press	0.08
versus 15L Press	-0.01
versus Avg Press	**0.10**
Cloud Cover:	
versus 9-18 skc	-0.33
versus 6-18 op skc	-0.39
versus 9-18 op skc	**-0.38**
Dew Point:	
versus Dew Pt 06L	-0.04
versus Max Dew Pt	-0.02
versus Avg Dew Pt	**-0.02**
Relative Humidity	
versus Avg RH 6-18	-0.43
versus Avg RH 9-18	**-0.43**
versus RH at 06L	-0.22
versus RH at 12L	-0.42
Wind:	
versus Avg Ws	**-0.47**
versus Max WS	-0.44
versus 06L WS	-0.39
versus 09L WS	-0.43

Upper Air:	12Z	00Z
versus 1000ft Temp	**0.33**	0.36
versus 2000ft Temp	0.27	0.35
versus 3000ft Temp	0.19	0.32
versus 4000ft Temp	0.13	0.28
versus 5000ft Temp	0.09	0.23
versus 1000ft WS	-0.34	-0.38
versus 2000ft WS	-0.41	-0.40
versus 3000ft WS	**-0.45**	-0.41
versus 4000ft WS	-0.45	-0.43
versus 5000ft WS	-0.42	-0.44
versus K-Index	0.03	0.07
versus Total Totals	0.00	0.05
versus Sweat Index	**-0.09**	-0.09



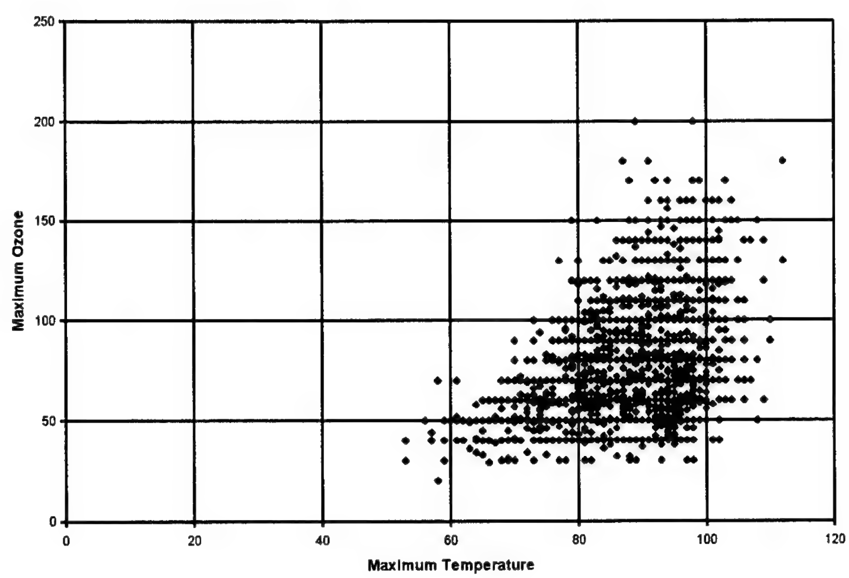


Fig. 17: Scatterplots of temperature vs. maximum ozone for Connecticut (top) and the DFW area (bottom). [Top figure adapted from NRC (1992).]

ozone values require high temperatures, only the Connecticut plot suggests that high temperatures lead to high ozone. The lack of linear relationship in DFW is due to a large number of high temperature, low ozone days, and the lack of cooler weather. Examination of scatterplots between temperature and other meteorological variables shows that, unlike in northern cities, high temperatures are not acting as a proxy for other ozone conducive conditions. For example, temperatures have exceeded 100 degrees with average daily cloud cover as high as 80% and wind speeds approaching 20 knots. As a result, the relationship between temperature and ozone is merely a rate limiting one. Temperature in the DFW area is only important until conditions are warm enough for the chemistry to proceed unhindered. Fig. 18 shows the correlation of temperature and ozone for each month of the season. This pattern is what one would expect from the above discussion. In the early and late season, temperature behaves more like it does in northern latitudes, but in mid-summer, temperatures are nearly always warm regardless of conditions, so temperature provides little information concerning daily maximum ozone.

Fig. 19 shows scatterplots of ozone with the remaining surface meteorological variables, including wind direction. While, as the correlation coefficients suggest, none show a strong linear relationship with ozone, all show some type of rate limiting relationship. High ozone values are clearly restricted to certain bounds. Unfortunately from a prediction stand point, being

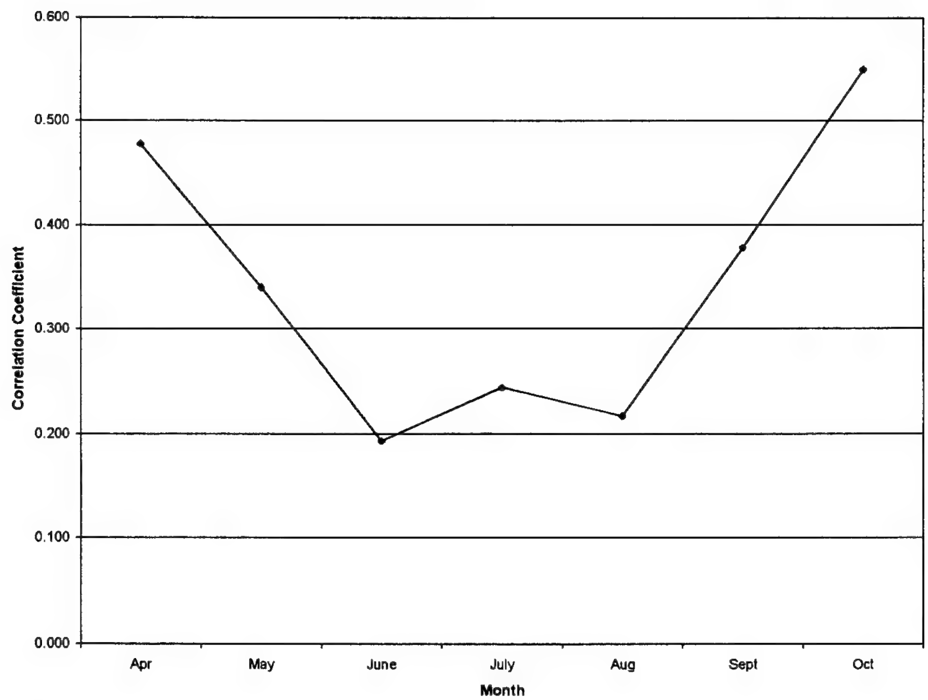


Fig. 18: Correlation between temperature and daily maximum ozone for each month of the season.

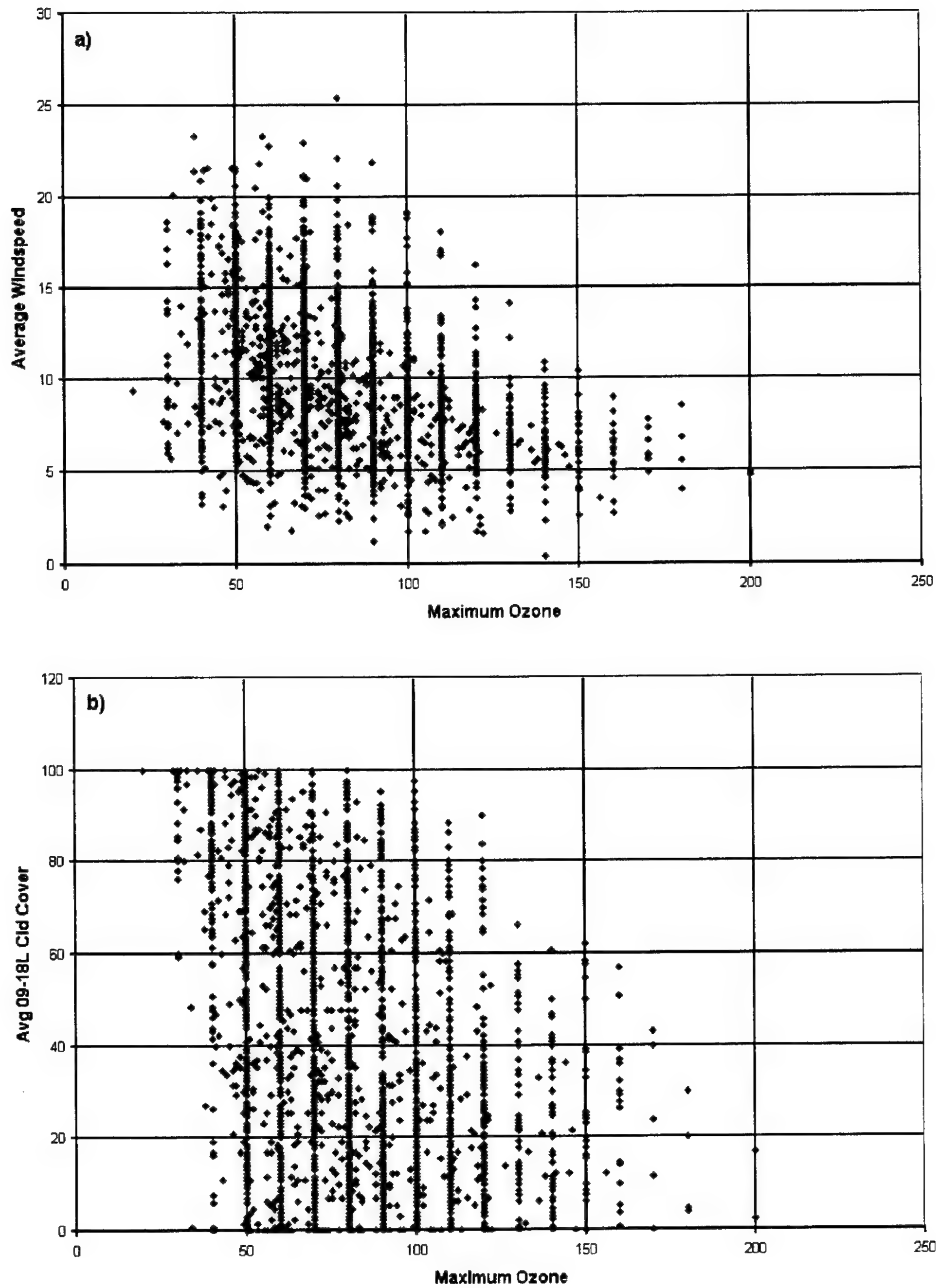
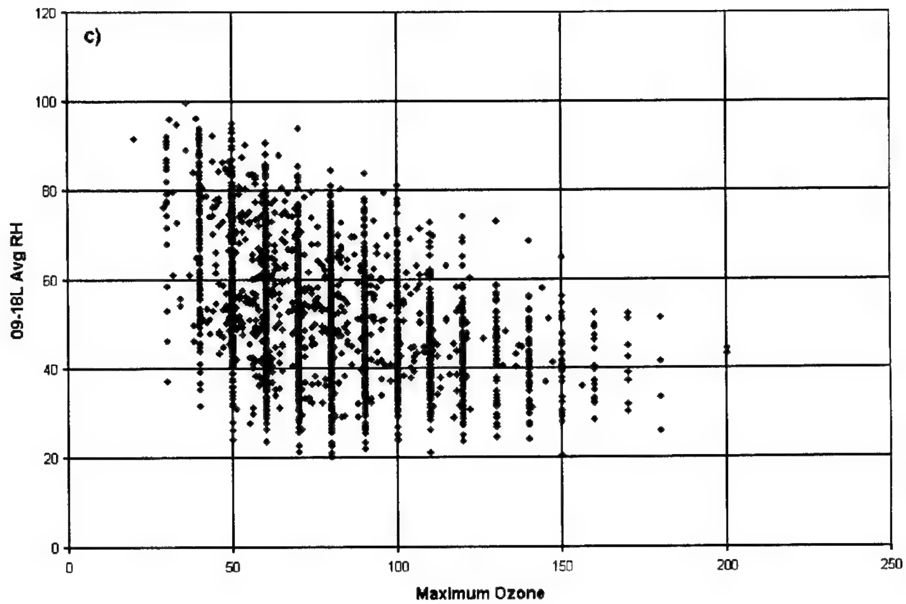


Fig. 19: Scatterplots of daily maximum ozone with: a) wind speed, b) cloud cover, c) relative humidity, d) pressure, e) dewpoint, and f) wind direction.


c)
09-18L Avg RH
Maximum Ozone
0
20
40
60
80
100
120
50
150
200
250

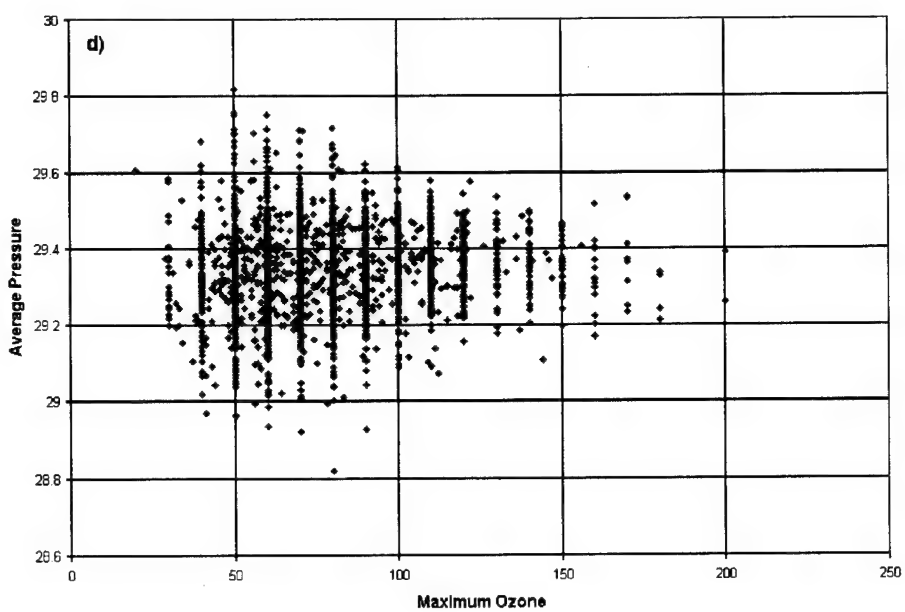
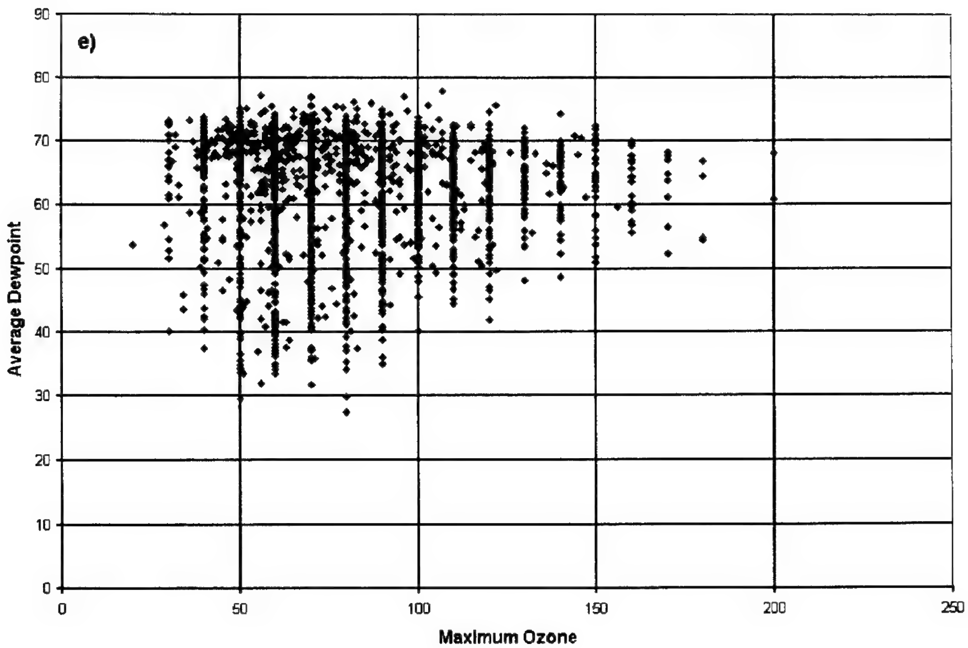

d)
Average Pressure
Maximum Ozone
28.6
28.8
29
29.2
29.4
29.6
29.8
30
0
50
100
150
200
250

Fig. 19: Cont.


e)
Average Dewpoint
Maximum Ozone
0
10
20
30
40
50
60
70
80
90
0
50
100
150
200
250

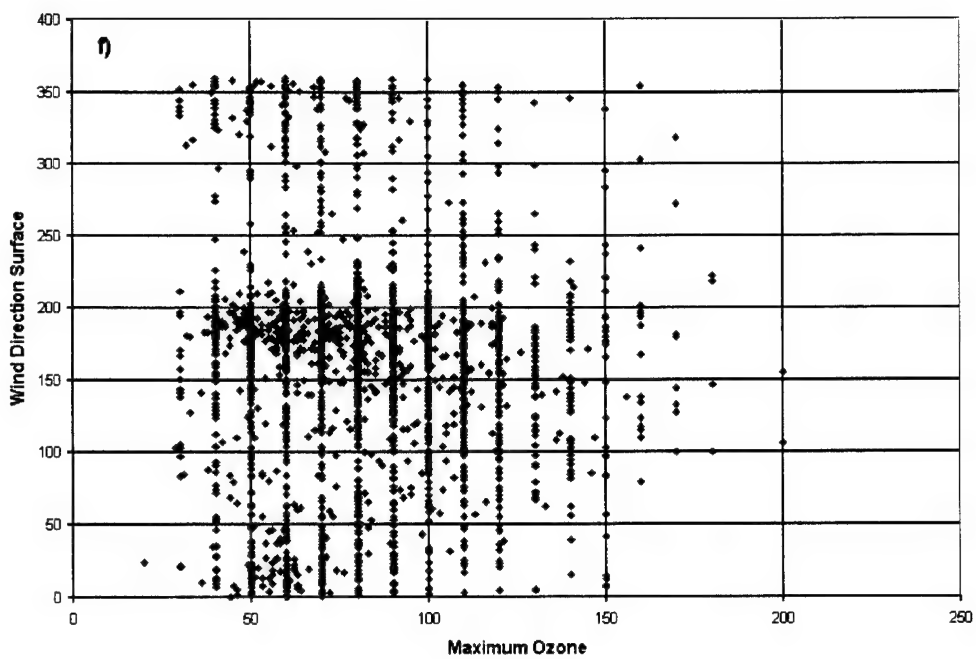

f)
Wind Direction Surface
Maximum Ozone
0
50
100
150
200
250
300
350
400
0
50
100
150
200
250

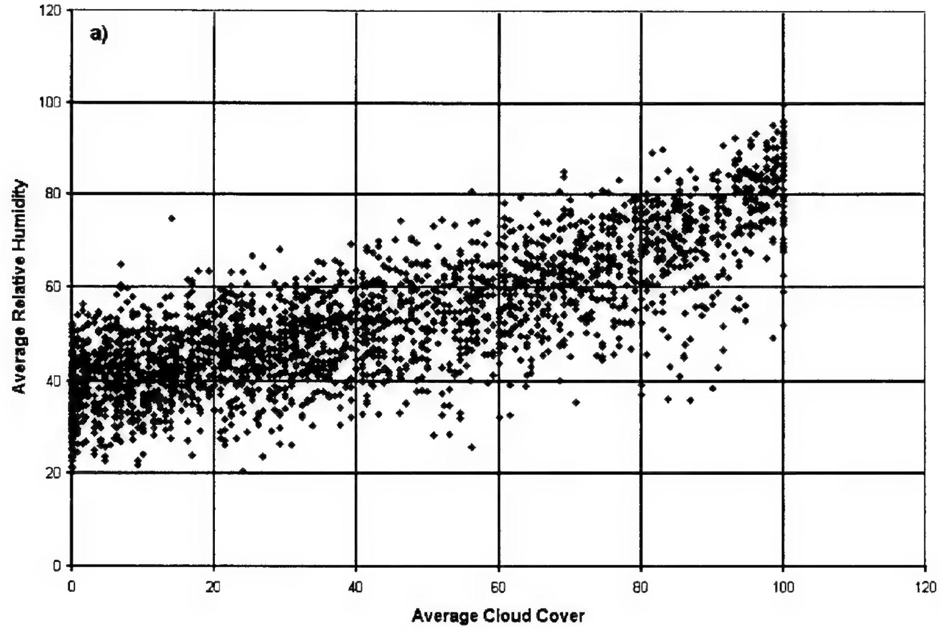
Fig. 19: Cont.

within those bounds by no means guarantees high ozone. Let's examine each variable.

Both wind speed and cloud cover show negative relationships with ozone as expected from chemistry considerations. Note however that high ozone values can occur with average daily cloud cover as high as 66%! A possible explanation could be due to an observational bias. Most of the summer cloud cover in the DFW area is convective in nature. Coverage could conceivably vary over relatively short space scales so that airport conditions may not be completely representative of the entire DFW area.

Relative humidity also displays a rate-limiting negative relationship with ozone and has the second highest correlation. The negative relationship is interesting. Most of the eastern U.S. experience high ozone when under the influence of the west side of a high pressure system, which usually implies higher relative humidity with high ozone. The scatterplots in Fig. 20 show that surface relative humidity in the DFW area has a strong positive relationship with cloud cover and a weaker, but still obvious, relationship with the Sweat Index possibly suggesting that relative humidity may in some way proxy for stability and percent of sunshine.

While both pressure and dewpoint show no statistically significant correlation with ozone, they do play a rate-limiting role. It is interesting that the highest and lowest pressure days are the least conducive to high ozone formation.



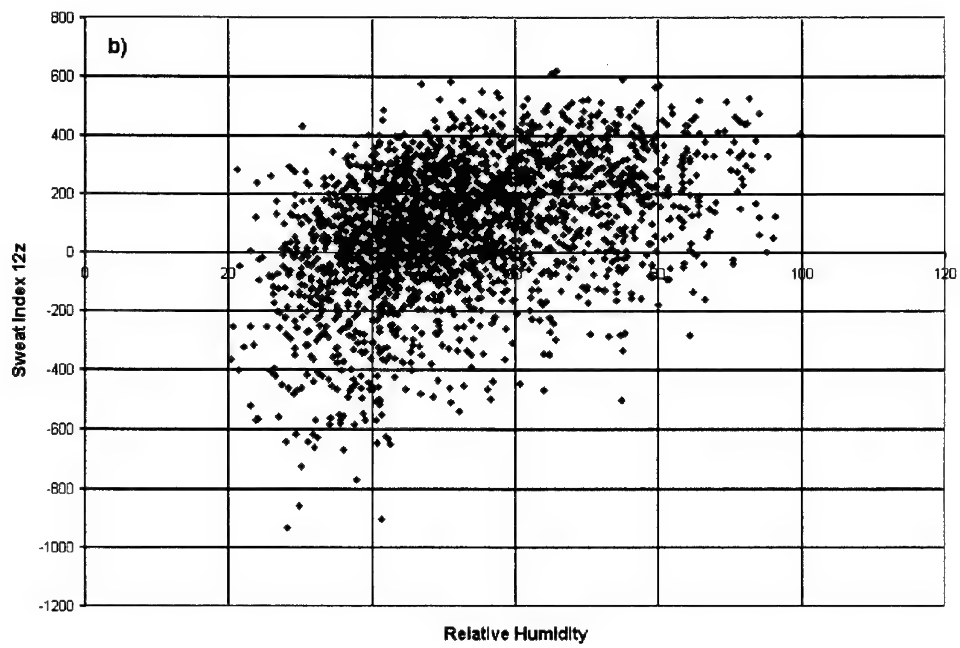


Fig. 20: Scatterplots of: a) daily average relative humidity vs. daily average cloud cover, and b) 12z sweat index vs. daily average relative humidity.

The wind direction scatterplot contains some very interesting information. Exceedences have occurred with winds from all cardinal directions, but the directions with a southerly component are clearly most favorable. This direction bias could be meteorological or network related. Winds from the east and southeast seem to show the largest percentage of exceedences as a group. Whatever the cause, wind direction clearly plays a significant role in determining the likelihood of an exceedence. This relationship will be explored extensively in the remaining sections.

Fig. 18 showed that the correlation of temperature with ozone varied throughout the season as the proxy relationship of temperature with other meteorological variables varied. Fig. 21 shows the seasonal variation of the other surface variables. In addition to temperature, wind speed cloud cover and relative humidity show strong seasonal variation. In terms of relative correlation behavior, the months of June, July, and August behave differently than the other months. The variability in correlation over the season is very significant and indicates that the proxy relationships of the meteorological variables are not static. This variation also probably contributed to the poor performance of the Cox and Chu (1993) model and offers a challenge to traditional regression based prediction.

Turning to upper air, the two variables most highly correlated with ozone from the morning (12z) sounding are the 1000ft temperature and the 3000ft

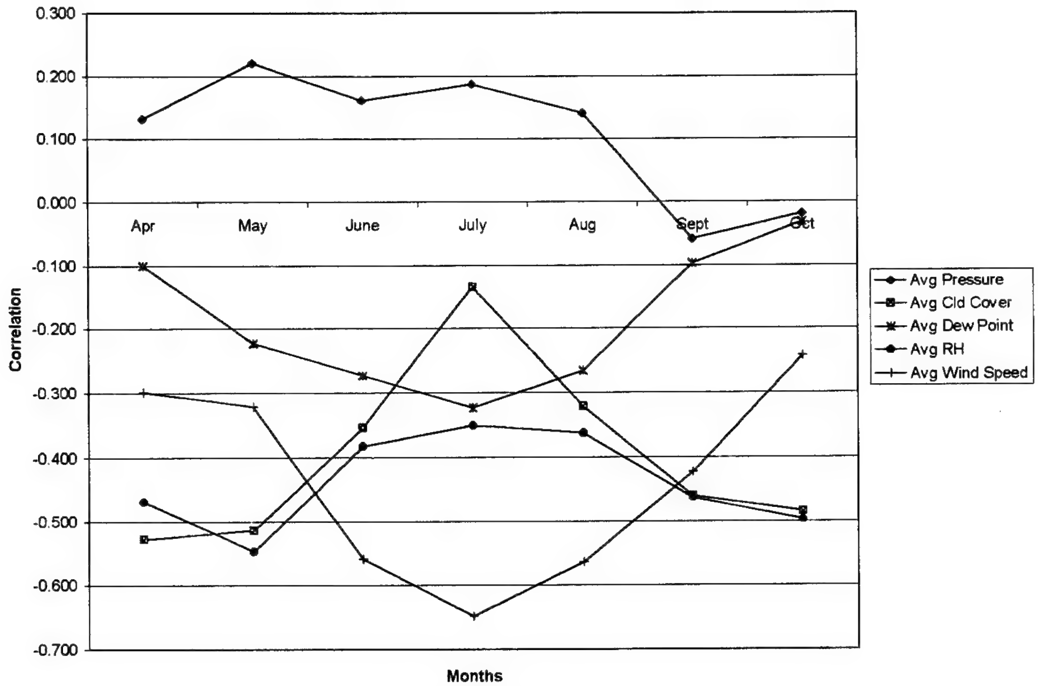


Fig. 21: Seasonal variation in correlation coefficient for several meteorological variables.

wind speed. Fig. 22 shows the scatterplots for these variables. Both relationships seem similar to their surface counterparts, but closer examination of temperature yields a difference. Fig. 23 shows correlation by month for the 1000ft temperature and 3000ft wind speed along with their surface counterparts. Note that while the wind patterns match, the temperature patterns seem de-coupled. Other studies have suggested that higher than normal upper level temperatures are indicative of downward moving air, thus restricted mixing heights. Under some conditions, the 12z 1000ft temperature could be performing in this manner.

Three stability indices were examined to assess the role of stability in hopes that one would provide a proxy for venting or mixing heights. None show a strong relationship with ozone although all three showed a rate-limiting role. The 12Z Sweat Index showed the best relationship of the three and is shown in Fig. 24. A rate-limiting relationship is observed, but the overall relationship is disappointingly weak.

In summary, unlike many other areas with high ozone problems, none of the meteorological variables selected for this study show a strong linear relationship with ozone. Instead, the variables display varying degrees of rate-limiting relationships. While bounds conducive to high ozone development can be identified for each variable, a wide range of ozone behavior is still possible within them. Additionally, the seasonal behavior of the correlation shows considerable variation for many of the variables. It is this probably a

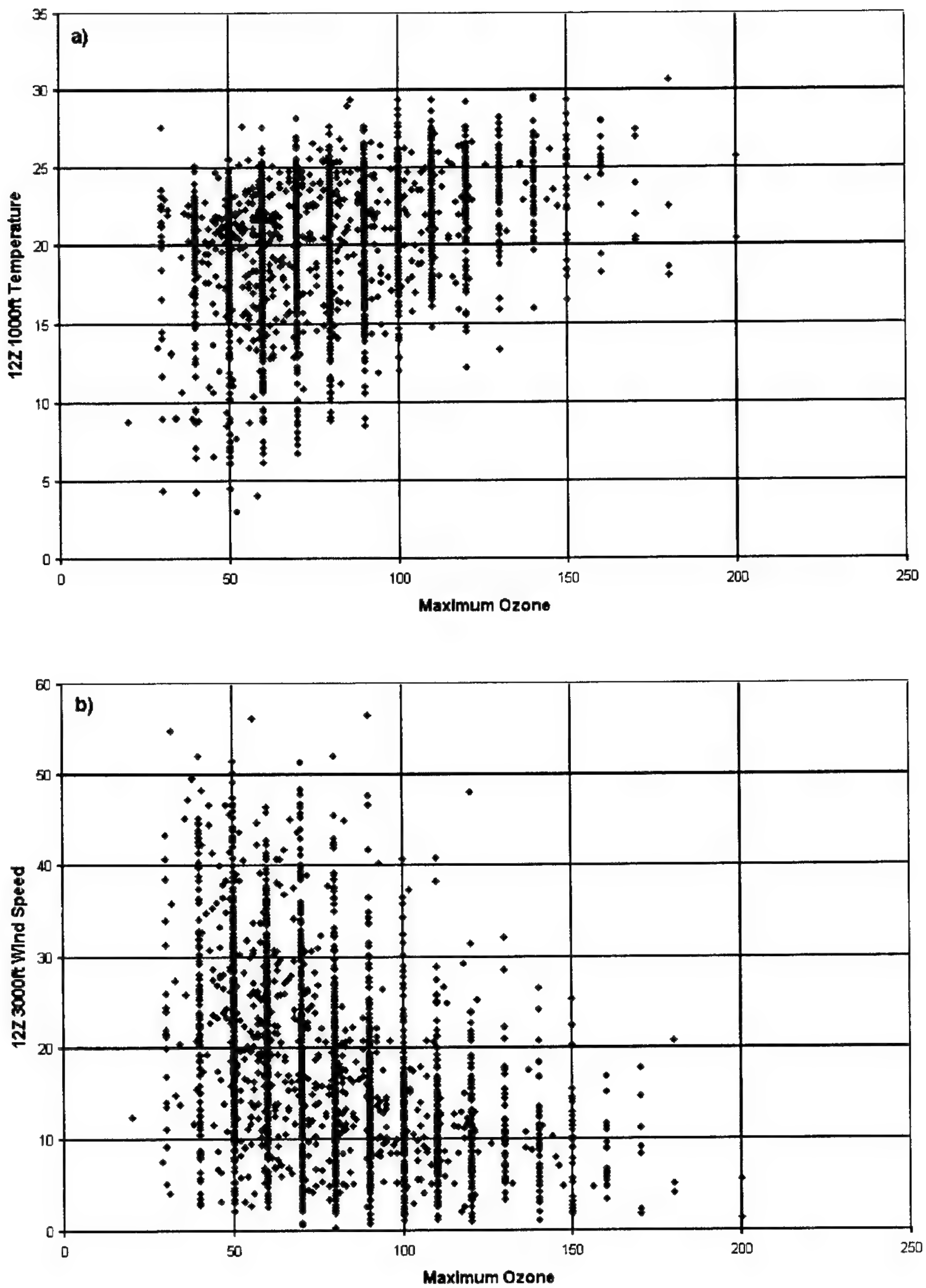


Fig. 22: Scatterplots of daily maximum ozone with: a) 12z 1000ft temperature, and b) 12z 3000ft wind speed.

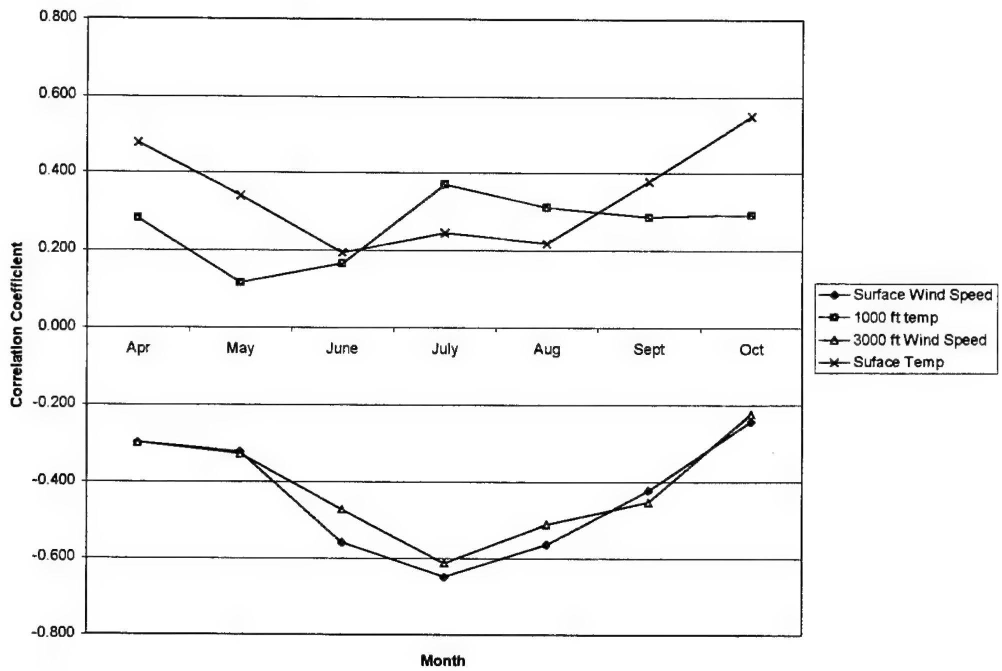


Fig. 23: Comparison of seasonal correlation variations between selected surface and upper air variables.

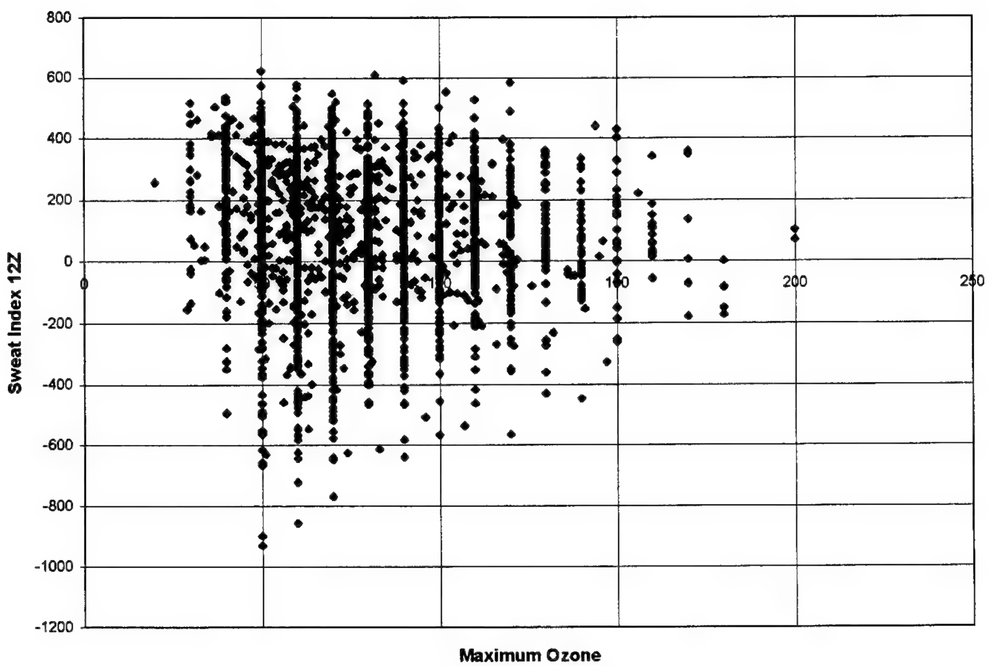


Fig. 24: Scatterplot of daily maximum ozone vs. 12z sweat index.

combination of these behaviors that accounts for the poor performance of the model used by Cox and Chu (1993) and suggests that ozone development in the DFW area is a highly non-linear process, owing to the complex relationship of the meteorological variables with each other.

4.2.2. Conditions Conducive to High Ozone Development

Using the results from the previous sections, CC tables were constructed to explore the conditions conducive to high ozone in the DFW area. The outline of CC Table construction was presented in section 3.2.2.. In order to create meaningful tables, it is necessary to consider both meteorological and non-meteorological factors.

The two non-meteorological factors considered here, that may play a role in the development of high ozone are the influence of yesterday's ozone and the northern bias of the DFW monitoring network. To account for the influence of YOZ, it was treated as a variable and broken into four categories: < 80 ppb, 80-104 ppb, 105-124 ppb, and > 124 ppb. The potential for a network spatial bias was considered by mandating the data split into two wind direction categories: Those with a southerly component and those without. It should be mentioned that a third non-meteorological factor could play a role. It is possible that there is a long-term trend in the data due to long-term changes in emissions. However, it is assumed that any trend will be small and no attempt will be made to account for it.

Next the meteorological variables were considered. The first category considered was the season itself. In the previous section, the months of June, July, and August were found to behave differently than the other months. Therefore, the first categories created were two seasonal ones. June, July, and August will be referred to as the High Ozone Season, while the remaining months will be termed the Fringe Ozone Season. Scatterplot matrices were created for each of the seasonal categories and the bounds of possible ozone exceedences were determined. Table 5 presents a comparison of bounds necessary for an exceedence for each sub-season vs. the full season. The favorable range of cloud cover and relative humidity are reduced in the fringe season while wind speed and dew point become more sensitive in the high season. Reducing the full season down to just days that fall within the possible exceedence bound of each variable, takes the number of days from 2745 to 1523. With 173 exceedences, these bounded conditions lead to an exceedence one out of ever nine days on average. Splitting into the two seasons and then reducing the data to the bounds for each season removes an additional 349 days. We are left with two seasons of potential high ozone days. For the fringe season this leaves 455 days with 33 days above 124ppb which gives a ratio of 1 exceedence for every 14 days within the bounds. For the high season there are 714 days with 140 exceedences or a one to five ratio.

Table 5: Meteorological bounds of days with ozone > 124 ppb for full, fringe, and high season.

		Range	
Variable	Full	Fringe	High
Wind Speed (kts)	0.4 - 14.1	3.5 - 14.1	0.4 - 10.9
Relative Humidity (%)	20.5 - 73.1	24.7 - 68.6	20.5 - 73.1
Temperature (F)	77 - 113	77 - 105	83 - 113
Dew Point (F)	48.2 - 74.2	48.2 - 74.2	51 - 72.4
Cloud Cover (%)	0 - 66	0 - 56	0 - 66
Pressure (in)	29.107 - 29.537	29.171 - 29.537	29.107 - 29.535
1000ft temperature (F)	13.4 - 30.7	13.4 - 28.3	18 - 30.7

For both seasons, three categories of predicted ozone were used: Days with ozone less than or equal to 104 ppb, days of 105-124 ppb, and days greater than 124 ppb. Specific meteorological categories were selected by examining the scatterplots for each variable from each season. As it turned out, the scatterplots from both seasons suggested wind speed, wind direction, relative humidity, and cloud cover would be the best variables to consider. Examination of the wind direction scatterplots suggested that winds from the east and southeast had a different relationship with ozone than winds from the south or southwest so a third direction category was added, splitting the southern directions into two categories. The non-southerly wind direction category was left alone to facilitate a network bias determination. The specific categories for the remaining variables were determined within each season.

a) Fringe Season: Based on the scatterplots, three categories of wind speed and two categories of relative humidity and cloud cover were used to construct the original tables. Category splits that did not provide useful information were recombined to limit the total number of splits. Splits that produced inconclusive results were subjected to splits with other meteorological variables (temperature, pressure, dewpoint, etc.) in an effort to find a reasonable split. As will be seen, this was not always possible.

Table 6 depicts ozone behavior following a day with maximum ozone less than or equal to 80 ppb. Only nine exceedences have occurred under these

conditions over the 15 years of the study. With a low input from the residual layer nearly ideal meteorological conditions are required in order to exceed 124 ppb. Indeed, wind speeds greater than 10 knots are clearly non-conducive. Winds of 7-10 knots are also very unlikely to produce exceedences, however winds from the east through southeast can produce high ozone values. The clear majority of exceedences come with light winds. Light winds, relative humidity less than 50%, and winds from 090-150 is the surest path to high ozone. Southerly winds will produce higher ozone values only when the vector wind speed is less than 4 knots. Winds from the non-southerly direction are not likely to produce high ozone, this could be a sign of network bias.

Table 7 presents results from days with yesterday's maximum ozone between 80-104 ppb. Only 9 exceedences have occurred in the 126 days that fit this category. It is interesting that the chosen wind direction categories did not work well here, but still there seems to be a bias towards non-southerly winds producing lower ozone readings given the same set of meteorological conditions. The best combination for an exceedence are winds less than 7 knots, relative humidity less than 50%, cloud cover less than 30% and wind direction between 120-240 degrees. In general higher wind speeds are less likely to produce high ozone, but some ambiguity is apparent in the 7-10 knot splits.

Table 8 shows behavior on days following ozone values of 105-124 ppb. In all, 10 exceedences have occurred over the 73 days in this category. Once

Table 6: CC Table for the Fringe Season following a day with ozone < 80 ppb.

YOZ: < 80ppb

	# Obs	< 104 ppb	104-124 ppb	>124 ppb
WS: <7knots:				
WD 250-090 degrees	28	68%	25%	7%
WD 090-150 degrees + RH<50%	9	0%	44%	56%
WD 090-150 degrees + RH>50%	7	71%	29%	0%
WD 150-250 degrees + VS<4kts	8	12%	63%	25%
WD 150-250 degrees + VS>4kts	11	91%	9%	0%
WS: 7-10 knots:				
WD 250-090 degrees	24	92%	8%	0%
WD 090-150 degrees	17	53%	41%	6%
WD 150-250 degrees	47	91%	9%	0%
WS: > 10 knots:				
	80	100%	0%	0%

Table 7: CC Table for the Fringe Season following a day with ozone 81-104ppb.

YOZ: 81-104ppb

	# Obs	< 104 ppb	104-124 ppb	>124 ppb
WS: <7knots:				
RH <50% + Cld Cover <30% + Wind Dir 120-240	10	10%	40%	50%
RH <50% + Cld Cover <30% + Wind Dir 241-119	11	45%	45%	10%
RH <50% + Cld Cover >30%	4	100%	0%	0%
RH >50%	13	69%	31%	0%
WS: 7-10 knots:				
Cloud Cover < 30%	33	54%	39%	6%
Cloud Cover > 30%	10	90%	10%	0%
WS: > 10 knots:				
	45	91%	7%	2%

Table 8: CC Table for the Fringe Season following a day with ozone 104-124ppb.

YOZ: 104-124 ppb

	# Obs	< 104 ppb	104-124 ppb	>124 ppb
WS: <7knots:				
Vector WS < 5 kts	15	0%	46%	54%
Vector WS > 5 kts	7	43%	43%	14%
WS: 7-10 knots:				
WD 251-149 degrees	11	64%	36%	0%
WD 150-250 degrees	16	56%	38%	6%
WS: > 10 knots:				
	24	96%	4%	0%

Table 9: CC Table for the Fringe Season following a day with an ozone exceedence.

YOZ: > 124 ppb

	# Obs	< 104 ppb	104-124 ppb	>124 ppb
WD 250-090 degrees	6	67%	33%	0%
WD 090-150 degrees	5	60%	20%	20%
WD 150-250 degrees	14	43%	36%	21%

again light winds are the surest sign of high ozone, and the vector wind speed improves the relationship. This time however, there is no directional bias. At intermediate wind speeds, no breakout was found that distinguished high ozone days from lower ones.

Table 9 is behavior following an exceedence day. This was quite surprising. No obvious breakout could be found for the likelihood of a second exceedence day. What can be said is that of the 25 days considered here only 4 exceeded, thus multiple exceedence days are rare during the fringe season. When they do occur, they have all had a southerly wind. Wind speed did not play a factor. The small number of repeat exceedences makes classification difficult.

Overall, light wind speeds seemed the surest way to get high ozone development, a wind direction of 090-150 was found more favorable to ozone development on days following maximum ozone of less than 105 ppb, while winds of 250-090 was generally less favorable to ozone development. The intermediate wind speeds were the hardest to get convincing splits for. Perhaps other meteorological variables not considered or long-term emission trends are complicating the analysis.

b) High Season: Again scatterplots were created and examined. Variables showing promise included wind speed, wind direction, relative humidity, and cloud cover. The number of categories used for each variable was the same as the fringe season, but the bounds were adjusted for both wind speed and relative humidity based on the scatterplots.

Table 10 is the CC Table when yesterday's ozone was less than 80 ppb. Again wind speed plays a dominant role in determining how high ozone can climb. High wind speeds (> 8 knots) and low ozone yesterday is a combination unlikely to result in high ozone development. The lowest wind speeds are required to get the best growth. Again the importance of the vector wind speed can be seen here. Intermediate winds (5-8kts) can still produce exceedences even though ozone was low yesterday. Here no obvious paths could be found for high likelihood of an exceedence, but again we see 090-150 wind direction is the most favorable for an exceedence. Winds of 150-250 will only be favorable when dew points are below 68F. Although not shown in the table, precipitation occurred on twelve days in this table. In every case, ozone failed to exceed 124 ppb.

Table 11 shows CC Tables for the 163 cases with ozone values of 80-104 ppb yesterday. Again high wind speeds combined with lower ozone from yesterday are unlikely to produce exceedences. Here light wind speeds are very rare, but cloud cover seems to make the difference under these circumstances. The low number of observations makes any conclusions difficult. Just as in the previous case, intermediate winds of 5-8 knots prove difficult to assess. Vector wind speed (VWS) clearly played a role in cases with wind direction other than 090-150. With winds of 090-150, relative humidity seemed to categorize well. Oddly, it is the 250-090 category that breaks out most definitively, however the light vector wind speed implies that the plume

Table 10: CC Table for the High Season following a day with ozone < 80 ppb.

YOZ: < 80ppb

	# Obs	< 104 ppb	104-124 ppb	>124 ppb
WS: <5knots:				
Vector WS <= 4 kts	13	15%	38%	47%
Vector WS > 4 kts	7	71%	29%	0%
WS: 5-8 knots:				
WD 250-090 degrees	42	60%	26%	14%
WD 090-150 degrees	20	30%	25%	45%
WD 150-250 degrees + DP <68F	32	59%	13%	28%
WD 150-250 degrees + DP >68F	24	83%	17%	0%
WS: > 8 knots:				
	167	94%	5%	1%

Table 11: CC Table for the High Season following a day with ozone 81-104ppb.

YOZ: 81-104ppb

	# Obs	< 104 ppb	104-124 ppb	>124 ppb
WS: <5knots:				
Cloud Cover <= 30%	8	25%	13%	62%
Cloud Cover > 30%	4	50%	50%	0%
WS: 5-8 knots:				
WD 250-090 deg + VWS*<5 kts	10	10%	20%	70%
WD 250-090 deg + VWS >5 kts	8	38%	62%	0%
WD 090-150 degrees + RH<45%	11	18%	36%	46%
WD 090-150 degrees + RH>45%	9	56%	44%	0%
WD 150-250 deg + VWS*<5 kts	13	23%	38%	38%
WD 150-250 deg + VWS >5 kts	11	91%	9%	0%
WS: > 8 knots:				
	89	72%	27%	1%

would not be advected very far south so the network would have still been capable of detecting the plume.

Table 12 is the CC Table for yesterday's ozone 104-124 ppb. Only eight cases of winds less than 5 knots occurred so they were grouped into the next category. Light winds are the simplest way to create an exceedence. Vector wind speed is important with 150-250 winds. Thanks to high YOZ, stronger winds can now lead to exceedences. The wind direction of 090-150 seems to offer an advantage. Wind directions of 150-250 have a few exceedences, but overall are unfavorable. Although not shown in the table, the 150-250 wind directions are associated with some of the highest dew points. Four out of five of the exceedences that did occur had dew points of less than 63F.

Table 13 presents the final CC Table, summer behavior the day following an exceedence. Of the 102 cases presented only 36 cases resulted in repeat exceedences. Wind speeds below 5 knots almost certainly produce an exceedence. Again wind speeds of 5-8 knots offer no clear path. Cloud cover offered some help, but wind direction, relative humidity, and vector wind speed failed to help. All that can be concluded is that conditions will almost always exceed 104 ppb. Wind speeds >8 knots are least likely to lead to a repeat. Here vector wind speeds make a significant difference. Worthy of note, but not included is the fact that the Sweat Index had an impact when wind speeds were greater than 8 knots. All nine repeat exceedences had 12z sounding

Table 12: CC Table for the High Season following a day with ozone 104-124ppb.

YOZ: 104-124 ppb

	# Obs	< 104 ppb	104-124 ppb	>124 ppb
WS: <8knots:				
WD 250-090 degrees	13	8%	31%	61%
WD 090-150 degrees	23	17%	26%	56%
WD 150-250 degrees + VS <5kt	17	0%	29%	71%
WD 150-250 degrees + VS >5kt	18	50%	33%	17%
WS: > 8 knots:				
WD 250-090 degrees	12	50%	33%	17%
WD 090-150 degrees + RH<50%	14	36%	21%	43%
WD 090-150 degrees + RH>50%	5	80%	20%	0%
WD 150-250 degrees	46	70%	20%	10%

Table 13: CC Table for the High Season following a day with an ozone exceedence.

YOZ: > 124 ppb

	# Obs	< 104 ppb	104-124 ppb	>124 ppb
WS: <5knots:				
	8	0%	12%	88%
WS: 5-8 knots:				
Cloud Cover < 30%	39	15%	44%	41%
Cloud Cover > 30%	15	27%	46%	27%
WS: > 8 knots:				
Vector WS < 8 kts	21	19%	38%	43%
Vector WS > 8 kts	19	63%	37%	0%

Sweat Indexes of <70. The vector wind speed was used however, since is showed an overall stronger relationship.

For the summer as a whole, similar themes to the fringe season was seen. Toughest calls are with intermediate wind speeds, wind directions of 090-150 again showed a likelihood for higher ozone, and the combination of YOZ, wind speed and wind direction were the most consistent predictors. Some bias against non-southerly winds was seen here, but it was not as obvious as in the fringe season.

4.3. Transportation of Ozone and Precursors

Station data presented in section 4.1 and the results of the CC Tables from section 4.2.2. demonstrate the importance of wind direction, and thus, ozone transport in the DFW area. Two aspects of transportation are considered here. First, understanding transportation of the local urban plume is important to the establishment of a cost effective and efficient monitoring network. Second, understanding the impact of long-range transport upon the area is essential if area ozone is to be restored to compliance.

4.3.1. Transport of the Local Urban Plume

Following the techniques of Chu (1995), vector averaged wind and pollution tables were constructed for the DFW area in an effort to assess direction bias in high ozone behavior (Table 14). The Pollution table consists of only those days with maximum ozone readings above 124 ppb. Looking at the wind table we see a strong directional bias for southerly winds in the DFW

Table 14: Vector wind (top) and pollution (bottom) roses. Winds < 3 knots are considered calm. Pollution rose is only for days with ozone > 124 ppb.

Calm: 10%

Direction	# obs	%obs	3-6 kts	7-12 kts	13-20 kts	>20 kts
N	139	5.1%	1.1%	3.3%	0.8%	0.0%
NNE	123	4.5%	1.4%	2.7%	0.3%	0.0%
NE	82	3.0%	1.1%	1.8%	0.1%	0.0%
ENE	58	2.1%	1.0%	1.1%	0.0%	0.0%
E	99	3.6%	2.2%	1.4%	0.0%	0.0%
ESE	120	4.4%	2.3%	2.1%	0.0%	0.0%
SE	178	6.5%	3.4%	2.9%	0.2%	0.0%
SSE	301	11.0%	3.3%	6.2%	1.5%	0.0%
S	846	30.8%	3.5%	16.6%	10.2%	0.5%
SSW	291	10.6%	2.0%	6.3%	2.3%	0.0%
SW	54	2.0%	0.6%	1.0%	0.1%	0.0%
WSW	28	1.0%	0.7%	0.3%	0.1%	0.0%
W	16	0.6%	0.4%	0.2%	0.0%	0.0%
WNW	28	1.0%	0.4%	0.4%	0.2%	0.0%
NW	36	1.3%	0.4%	0.8%	0.2%	0.0%
NNW	71	2.6%	0.6%	1.4%	0.6%	0.0%

Calm: 39%

Direction	# obs	%obs	3-6 kts	7-12 kts	13-20 kts	>20 kts
N	3	1.7%	1.2%	0.6%	0.0%	0.0%
NNE	2	1.2%	1.2%	0.0%	0.0%	0.0%
NE	1	0.6%	0.6%	0.0%	0.0%	0.0%
ENE	2	1.2%	0.6%	0.6%	0.0%	0.0%
E	15	8.7%	6.9%	1.7%	0.0%	0.0%
ESE	14	8.1%	6.4%	1.7%	0.0%	0.0%
SE	19	11.0%	9.2%	1.7%	0.0%	0.0%
SSE	9	5.2%	4.6%	0.6%	0.0%	0.0%
S	21	12.1%	8.7%	2.9%	0.6%	0.0%
SSW	9	5.2%	2.9%	2.3%	0.0%	0.0%
SW	6	3.5%	2.9%	0.6%	0.0%	0.0%
WSW	4	2.3%	1.2%	1.2%	0.0%	0.0%
W	0	0.0%	0.0%	0.0%	0.0%	0.0%
WNW	0	0.0%	0.0%	0.0%	0.0%	0.0%
NW	0	0.0%	0.0%	0.0%	0.0%	0.0%
NNW	0	0.0%	0.0%	0.0%	0.0%	0.0%

area with a secondary maximum from the north. Winds from the westerly directions are the rarest. Turning to the pollution table some interesting differences are seen. First, note the increase in easterly through southeast sector, more evidence of a directional bias in favor of high ozone days from this direction. Next, note that northerly winds decrease significantly. There are two possible suggestions for the reduction in likelihood. First, these directions could be associated with meteorological conditions unfavorable to ozone development. Second, the lack of long-term instrument monitoring downwind of the cities from these directions could be biasing the pollution table. The results from the CC Tables already suggest that the later is more likely, but Chu (1995) suggests testing this by building a pollution rose using just days that are suspected to be conducive to ozone development. For this, the high season reduced data set used in the construction of the CC Tables was used. Clearly not all of these days produced high ozone, but nearly 1/2 recorded values in excess of 104ppb and all were within the bounds identified as necessary for exceedence ozone development. Table 15 shows the resulting wind table. Winds from every direction are possible with these conditions, thus non-southerly winds can occur with conditions conducive to ozone formation. It is possible that high ozone conditions have occurred (or are occurring) and the network configuration is failing to record them. Turning specifically to the north we see some reduction in observations with this wind table, but it still suggests that the pollution table shows a larger than expected drop in northerly

Table 15: Pollution rose of days considered conducive for ozone formation. Winds < 3 knots are considered calm.

Calm: 14%

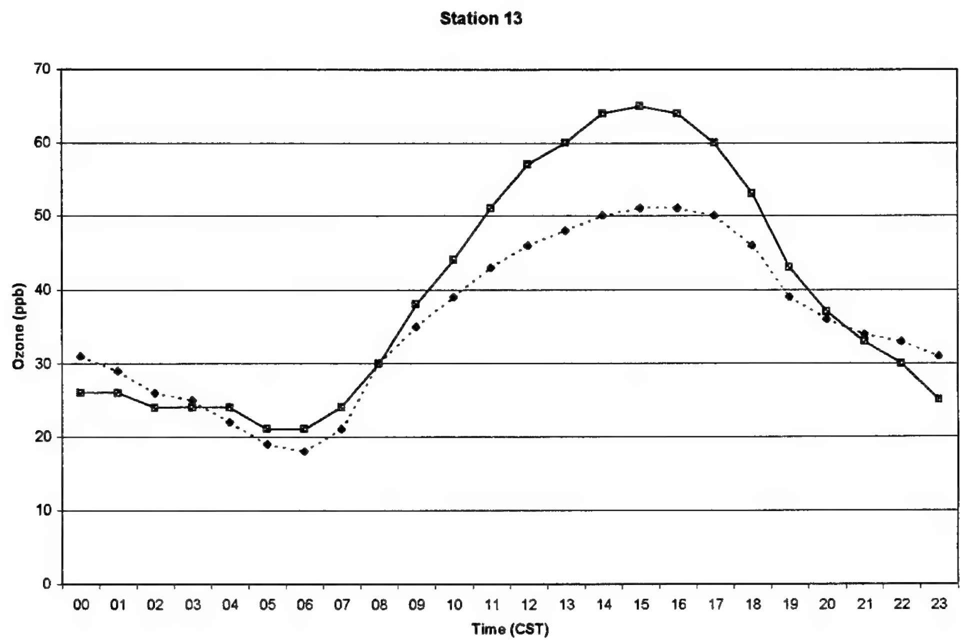
Direction	# obs	%obs	3-6 knts	7-12 knts	13-20 kts	>20 kts
N	20	2.8%	1.1%	1.8%	0.0%	0.0%
NNE	19	2.6%	1.4%	1.3%	0.0%	0.0%
NE	12	1.7%	1.0%	0.7%	0.0%	0.0%
ENE	10	1.4%	0.8%	0.6%	0.0%	0.0%
E	42	5.8%	3.8%	2.1%	0.0%	0.0%
ESE	31	4.3%	1.9%	2.4%	0.0%	0.0%
SE	50	7.0%	4.2%	2.8%	0.0%	0.0%
SSE	72	10.0%	5.0%	5.0%	0.0%	0.0%
S	216	30.1%	7.5%	22.6%	0.6%	0.0%
SSW	103	14.3%	4.3%	10.0%	0.0%	0.0%
SW	18	2.5%	1.0%	1.5%	0.0%	0.0%
WSW	10	1.4%	1.0%	0.4%	0.0%	0.0%
W	4	0.6%	0.6%	0.0%	0.0%	0.0%
WNW	2	0.3%	0.1%	0.1%	0.0%	0.0%
NW	2	0.3%	0.3%	0.0%	0.0%	0.0%
NNW	7	1.0%	0.4%	0.6%	0.0%	0.0%

exceedences. The recent establishment of a continuous monitor to the south in Midlothian is a good addition to the network.

In summary, the wind table suggests winds most often blow on a north-south axis through the DFW area. Winds from the north can be conducive to ozone development, but monitoring to the south of the city has not been continuous. The pollution table suggests that urban plumes can be expected to produce ozone while moving to the south of the area. The ozone monitor located in Midlothian is a good addition to the monitoring network. Wind tables and evidence from section 3 suggests that the urban plume does advect to the east and west of the area on rare occasions. When it does it is likely that the current network is not detecting the highest ozone readings.

4.3.2. Long-Range Transport of Precursors and Ozone

To examine the potential effect of long-range transport upon the DFW area, the diurnal behavior of upwind vs. downwind days were compared at the periphery sites around the DFW area. Figures 25 through 28 present the diurnal behavior of southern, northern, western, and eastern sites respectively. The dashed curve is for days classified as upwind while the solid curve represents downwind days. Upwind and downwind were determined relative to the DFW Metro-plex. For stations south, west, and north effects of the urban plume can clearly be seen. Upwind days at both northern and southern sites are very similar with average afternoon readings in upper 50's. In the west, very low ozone readings are observed on upwind days. In the east something



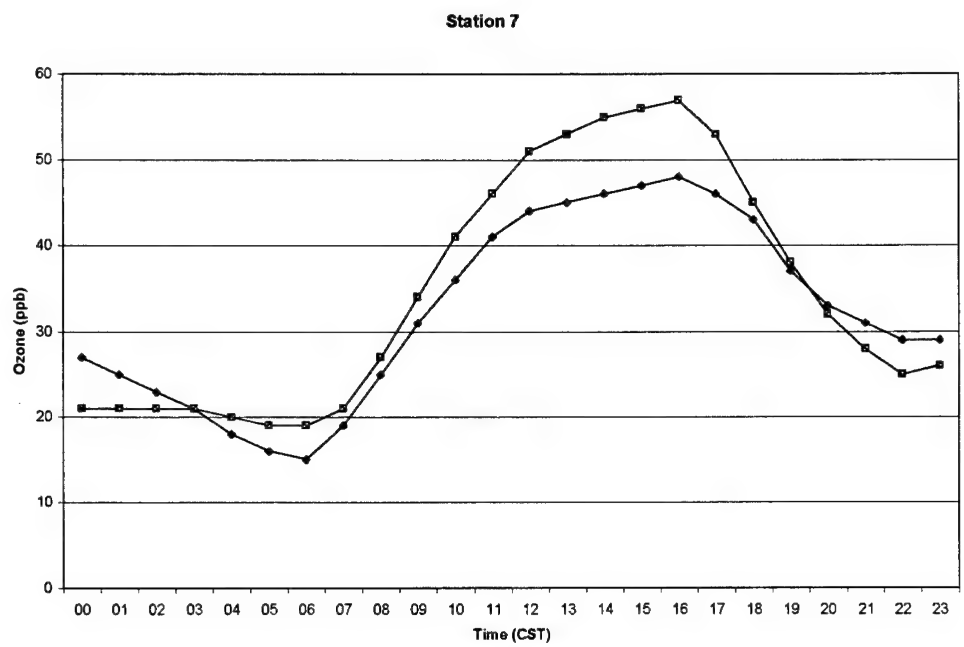
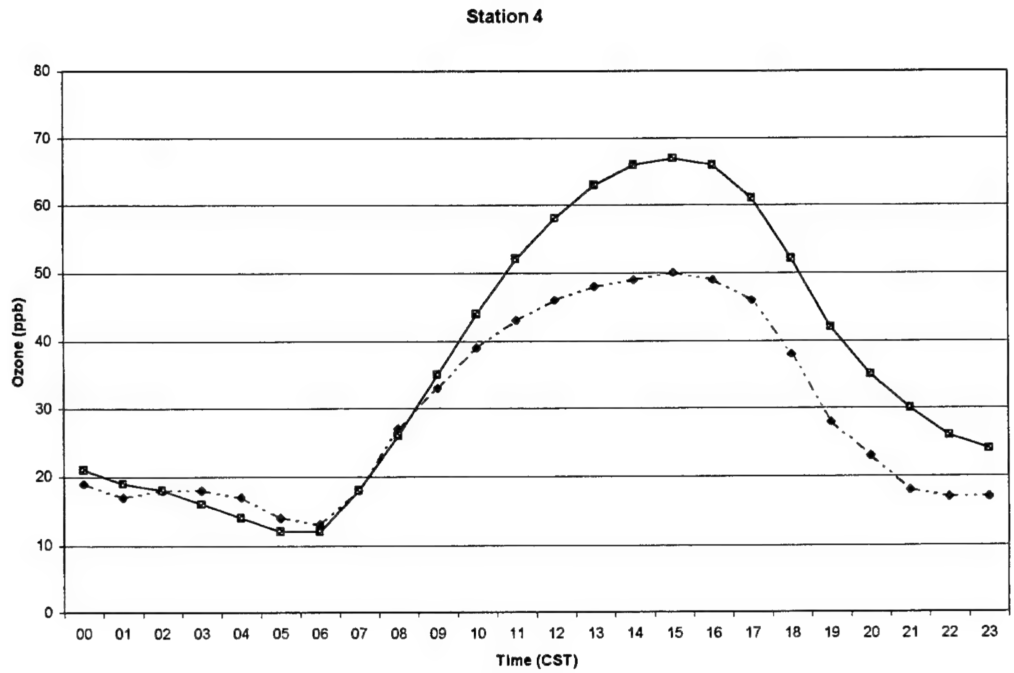


Fig. 25: Comparison of diurnal behavior for southern sites on upwind (diamonds) vs. downwind (squares) days. Upwind / downwind determined relative to the DFW metro-plex.



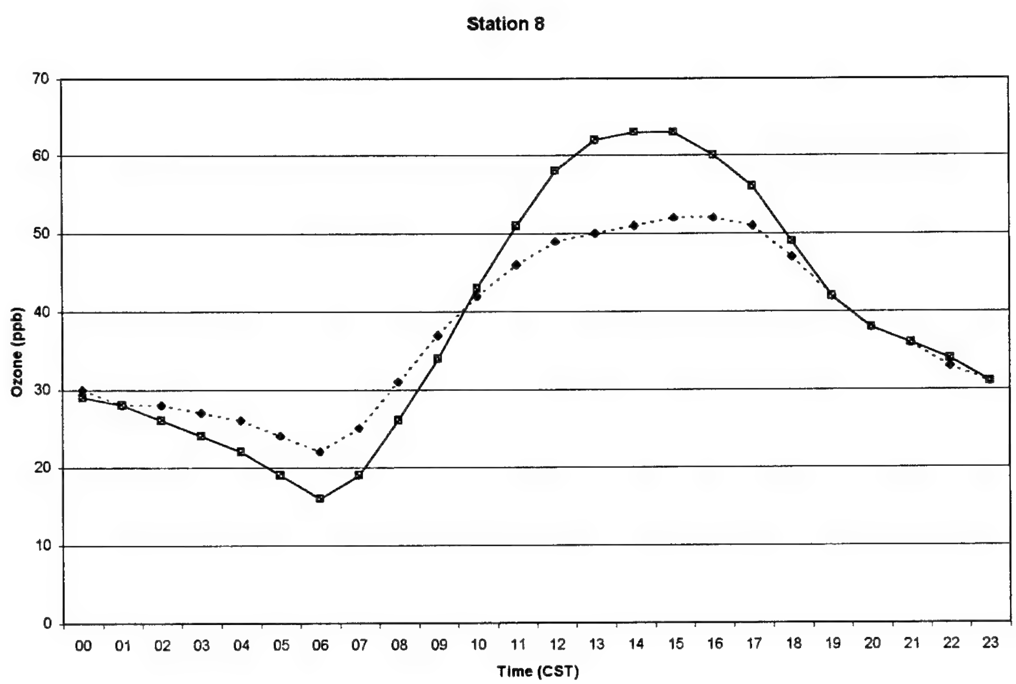


Fig. 26: As in Fig. 25 except data is for northern sites.

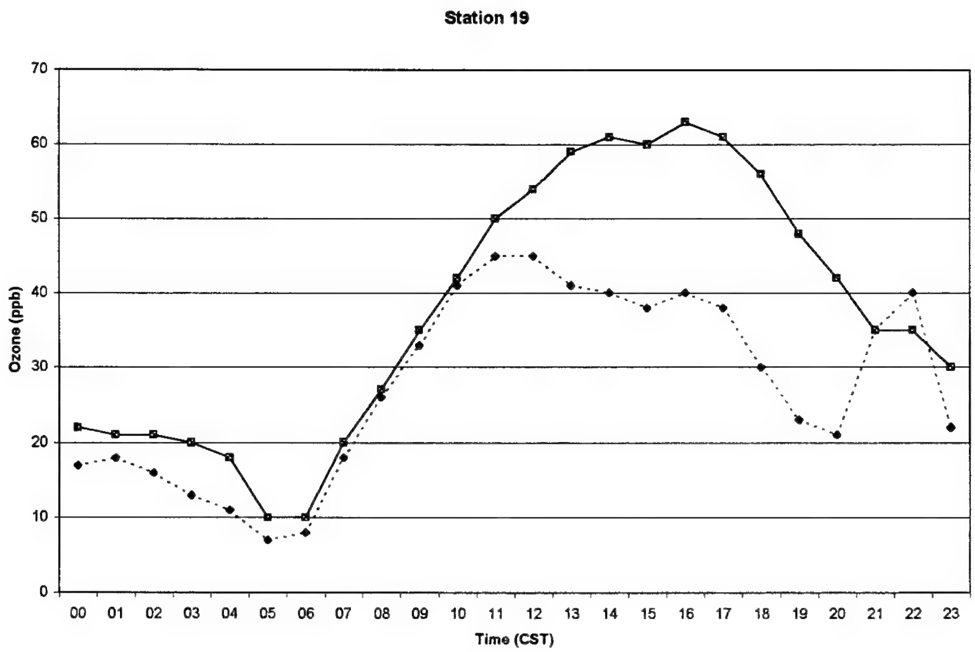
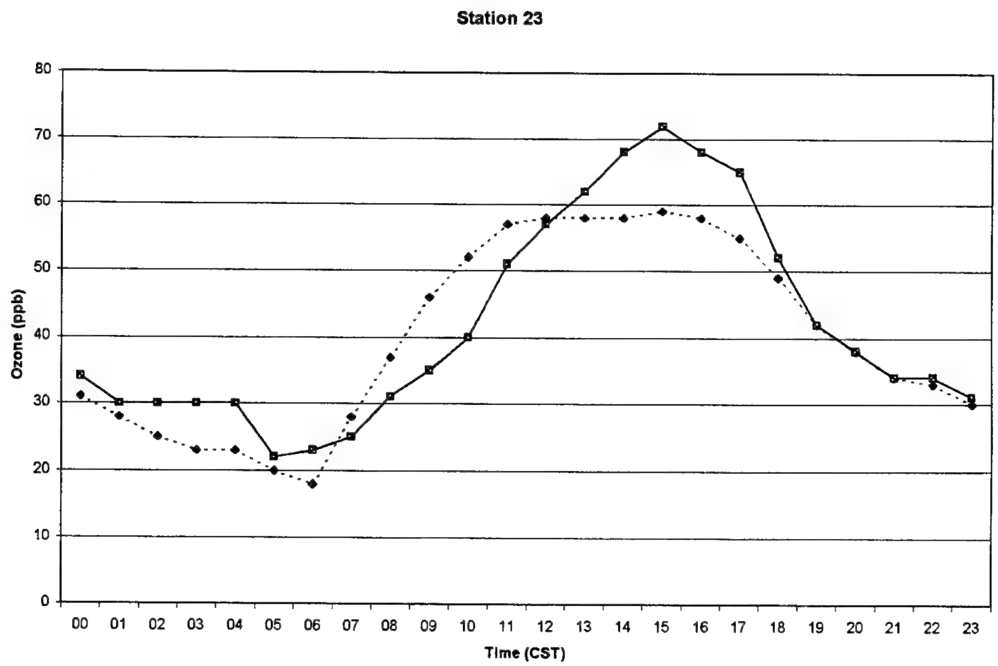


Fig. 27: As in Fig. 25 except for the western site.



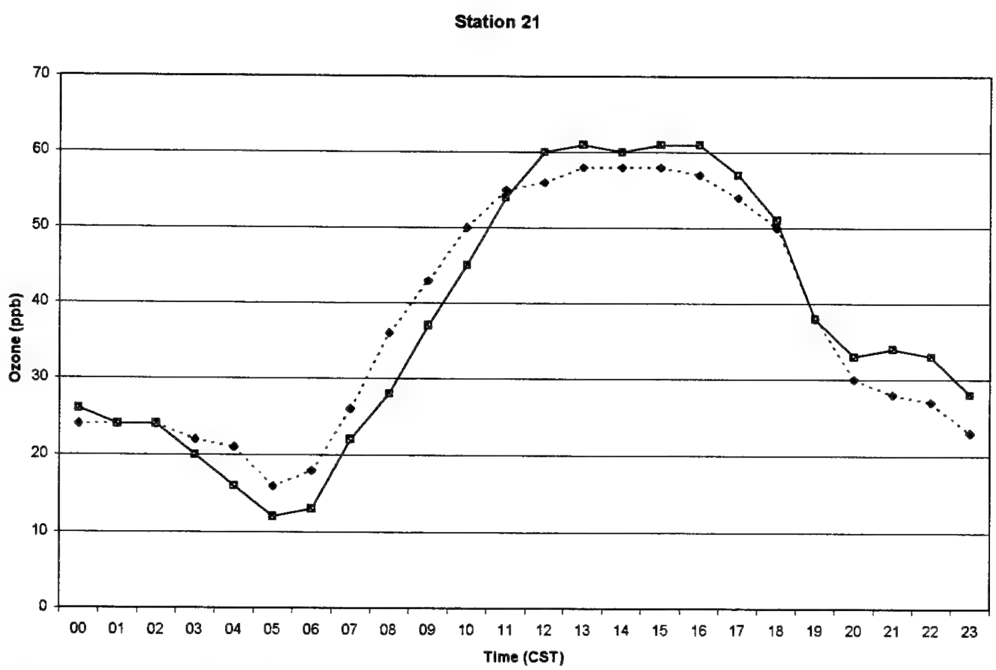


Fig. 28: As in Fig. 25 except for western sites.

different is happening. Both sites have much higher ozone readings on upwind days than seen in the other sectors. Also, station 21 shows no difference between upwind and downwind days. Data for the two stations was examined more closely. At station 23 there were 43 cases of upwind behavior classified as a vector wind direction of 45-135 degrees. From this direction, 19 days recorded a maximum of 70 ppb or greater. Eight days had a maximum of 90 or above. In each of these cases the wind direction ranged from 070-135 degrees. This would imply a transport of precursors from this direction. Fig. 2 shows there are no significant local point sources in this area, however, in this case it may be local since the city of Terrel is located to the southeast of the monitor location. Station 21 had a total of 15 days at or above 70 ppb with wind a direction of 045-135 degrees. Ten of the days occurred with winds 070-135 in direction, two of which exceeded 90 ppb. There are no large communities to the E or SE of this monitor location. As a further check, the behavior of station 7 which was located to the south of Dallas was checked to see how it behaved during easterly and southeasterly winds. There were 37 days of winds with 070-135 degree directions. Fifteen of these days saw ozone reach or exceed 70 ppb. Four of the days exceeded 90 ppb. However, the city of Ennis lies to the southeast of the location that the monitor used to sit at, and may be responsible.

The fact that two of the monitors examined have communities in the direction that elevated ozone levels occur from complicates the interpretation of

transport from the east. Even if stations 7 and 23 were impacted by their local communities, station 21 still suggests that something may be happening. Also, the CC Tables and pollution roses constructed in this study clearly showed a directional preference of 090-150 for high ozone episodes. While far from conclusive, there is at least some evidence that wind flow from the east through southeast is enhancing ozone levels in the DFW area. If this is the case, it is unclear where the source of this transport is. Additional monitoring in remote locations to the east or southeast of the area would provide additional information.

5. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to present a basic analysis of the DFW ozone problem and to compare its characteristics with similar studies in other parts of the country. The major findings of this study are:

The DFW high ozone season extends from 15 Apr - 15 Oct, and variations within this season are clearly observed. As a result, treating the season as a single entity may produce unwanted influence from the annual cycle. This season is about one month longer than the traditional season used in the more northern latitude cities of the U. S.

Ozone behavior exhibits strong episodic tendencies on the synoptic timescale. This is evident in multi vs. singular high ozone day statistics and in the correlation of today's ozone with yesterday's. This is typical of many other cities studied in the U. S. and around the world.

The lack of a consistent monitoring network makes spatial studies challenging, but in general, spatial ozone behavior is typical of other urban areas with relatively depressed ozone values in the urban area and increasing ozone values in rural areas downwind. The urban plume most often impacts areas to the north of the metro-plex, but plume movement in all four cardinal directions is supported at least occasionally.

Daily maximum ozone's relationship with meteorology showed some surprising differences from studies in other cities. None of the meteorology variables showed a strong, or even moderate, correlation with ozone. Instead,

all of the variables displayed some form of rate-limiting relationship. Temperature, which is so strongly correlated in many of the northern cities of the U. S., fails to proxy for photochemical conducive conditions in the DFW area and is therefore weakly correlated here. In addition, many of the correlation coefficients show significant seasonal variations suggesting that proxy relationships among the meteorological variables are not static. Overall, wind speed and relative humidity show the best correlation with maximum ozone. The combination of poor linear correlation and changing correlation through the season is what probably lead to the poor performance of the Cox and Chu (1993) model.

Conditional Climatology (CC) Tables were used as a tool for exploring the conditions most conducive to high values of daily ozone. Combinations of YOZ wind speed and wind direction proved the most powerful predictors. Other surface meteorological variables were helpful occasionally, but upper air variables failed to provide any significant contribution to the CC Tables. The remote location of the sounding site (70 miles southwest) during this study period may have been a factor. Several intermediate wind speed cases could not be broken out conclusively suggesting other factors not considered here played a role. Wind directional biases from the E through SE and from the non-southerly directions were present. The non-southern bias is probably related to the spatial bias of the surface network and indicates that plumes moving in a direction other than north would not be detected consistently.

The E through SE bias seen in the CC Tables was examined by comparing upwind vs. downwind diurnal ozone behavior at each of the periphery sites around the DFW area. Upwind behavior at the easterly sites differed from upwind behavior at sites in other directions suggesting that there may be a component of long-range transport entering the DFW area from this direction. Further study on this possibility is recommended.

The following are recommendations for areas of further research:

Conduct similar studies in the other southern cities that performed poorly in the Cox + Chu (1993) study to yield a more complete understanding of why southern cities did not perform well.

A PCA or synoptic weather classification scheme as a method of analysis in the DFW area may be a more effective way at characterizing the relationship of ozone and meteorology, especially the conditions most conducive to high ozone formation.

Finally, conduct a monitoring study in a remote rural area to the east or southeast of the DFW area. This, combined with the previous recommendation would better assess the possibility of long-range transport from this direction.

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